

~~CONFIDENTIAL~~

Copy 268
RM E54K26

USAF TECHNICAL LIBRARY
HOLLOMAN AIR FORCE BASE
ALAMOGORDO, NEW MEXICO

72 OCT 1955

NACA

TECH LIBRARY KAFB, NM
0144075

RESEARCH MEMORANDUM

INLET-AIR DISTORTION EFFECTS ON STALL, SURGE, AND

ACCELERATION MARGIN OF A TURBOJET ENGINE

EQUIPPED WITH VARIABLE COMPRESSOR

INLET GUIDE VANES

By David P. Harry, III, and Robert J. Lubick

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

CLASSIFIED DOCUMENT

This material contains information affecting the National Defense of the United States within the meaning of the espionage laws, Title 18, U.S.C., Secs. 793 and 794, the transmission or revelation of which in any manner to an unauthorized person is prohibited by law.

**NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS**

WASHINGTON

October 4, 1955

~~CONFIDENTIAL~~

NACA RM E54K26

6905



0144075

NACA RM E54K26

~~CONFIDENTIAL~~

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

INLET-AIR DISTORTION EFFECTS ON STALL, SURGE, AND
ACCELERATION MARGIN OF A TURBOJET ENGINE EQUIPPED
WITH VARIABLE COMPRESSOR INLET GUIDE VANES

By David P. Harry, III, and Robert J. Lubick

SUMMARY

The turbojet engine was investigated in an altitude test chamber at the NACA Lewis laboratory to determine the effects of a wide range of uneven inlet-air pressure distributions on transient characteristics and stall phenomenon. Circumferential, radial, and mixed pressure variations were run at simulated altitudes of 15,000, 35,000, and 50,000 feet at a simulated flight Mach number of 0.80.

In the range investigated, circumferential distortions did not change the span-wise blade loading or seriously impair operation. Surge occurred when any segment of the compressor reached the undistorted surge pressure ratio. Radial distortions with low pressure at the rotor blade tip increased the loading in a region that was normally heavily loaded. Serious reductions in acceleration margin resulted; slightly larger distortions than those investigated may completely prevent acceleration. Inverse radial (low pressure at the hub) distortions increased acceleration margin at lower speeds, though some reductions occurred at high speeds. Mixed (combination circumferential and radial or inverse radial) distortions produced changes similar to the corresponding radial distortion alone.

INTRODUCTION

Space or structural limitations often compromise the design of inlet ducting in turbojet engine installations. Severe bends or rapid diffusion of the air entering the engine result in uneven pressure distributions, or distortions, particularly during unusual flight conditions such as high angle of attack or yaw. Subsonic inlet ducts in service often produce distortions of 10 to 15 percent total-pressure variation at the compressor inlet. In most cases the distortion is a combination of circumferential and radial gradients. Engine performance losses and operational problems including surge, blow-out, or structural failure may result from these gradients. An example of engine failure due to inlet-air distortion is discussed in reference 1.

~~CONFIDENTIAL~~~~CONFIDENTIAL~~

2-77

UQ-1

A program has been established at the NACA Lewis laboratory to study the effects of distortion on various turbojet engines. Investigations carried out to study the effects of distortions on the steady-state and operational characteristics of several turbojet engines are reported in references 1 to 3. As a part of this program an investigation has been made of the effects of distortion on a single spool, high-pressure-ratio axial-flow turbojet engine with variable compressor inlet guide vanes. For the data presented herein, only the effects on transient characteristics and stall phenomenon are discussed.

Specifically, the object of the study reported herein was to determine the effects of inlet-air distortion on the surge, stall, and acceleration characteristics of the engine with both closed and open positions of the variable inlet guide vanes. In addition, the stage and blade element performance of the compressor was examined to obtain an understanding of the surge and stall characteristics of the engine. Four simple types of distortion selected for the study reported herein are:

- (1) Radial (low pressure at outer annulus of compressor)
- (2) Inverse radial (low pressure at hub)
- (3) Circumferential (symmetrical about a compressor diam.)
- (4) Mixed distributions (circumferential with either radial or inverse radial distortions)

Data were obtained at simulated altitudes of 15,000, 35,000, and 50,000 feet at a simulated flight Mach number of 0.80. The investigation covered a range of engine speeds from 55 to 105 percent of rated with the variable inlet guide vanes either open or closed. Only data obtained with the rated area exhaust nozzle are presented herein.

Pressure ratio margin, the difference between steady-state and surge pressure ratios, is used as an indication of the changes in the ability of the engine to accelerate. Discussions of the effects on surge and stall phenomena and compressor aerodynamics are included.

APPARATUS

Engine

A view of the experimental turbojet engine in the altitude test chamber is shown in figure 1. The engine has variable inlet guide vanes, a 12-stage axial-flow compressor, a cannular-type combustor, and a two-stage axial-flow turbine. For this investigation it was equipped with a clam-shell-type variable-area exhaust nozzle. The engine performance is presented in reference 4. The static sea-level military rating with inlet guide vanes open is:

~~CONFIDENTIAL~~

Engine speed, rpm 7950
 Exhaust gas temperature, °F 1185
 Thrust, lb 8920
 Specific fuel consumption, (lb)(hr)/lb thrust 0.917

The compressor has a tip diameter of $32\frac{1}{8}$ inches and a rated pressure ratio of 6.9 at rated speed. The hub-tip ratios at the first and twelfth stages are approximately 0.455 and 0.88, respectively. The 21 variable inlet guide vanes (incorporated to avoid surge) rotate 30° from the open to the closed position. In the open position, the angle between the engine center line and a tangent to the leading and trailing edges is 0° at the root and 13° at the tip of the blade. The engine manufacturer scheduled the guide vanes to begin opening at 6000 to 6300 rpm and reach the open position at 7000 to 7300 rpm as speed is increased, and inversely as speed is decreased. For this investigation manual operation was substituted to extend the range of operation in either open or closed position.

Instrumentation

The location of instrumentation throughout the engine is shown by the sketch in figure 2. The type, quantity, and response rates of transient instruments are listed in table I. During the investigation, calibrations of transient equipment were obtained from steady-state values photographically recorded.

The transient responses of the engine parameters were recorded on a six-channel, direct inking, magnetic motor oscillograph.

Qualitative measurements of air flow fluctuations were obtained through the use of 1-mil hot-wire anemometers installed in the first, sixth, and twelfth stator rows of the compressor at variable heights in the flow passage. The signals, a function of specific mass flow $f(\rho V)$, were observed on oscilloscopes as well as recorded on high-speed photographic paper by a galvanometric oscillograph. This instrumentation, used for analysis purposes in connection with the frequency and relative magnitude of rotating stall and surge phenomena, was not calibrated to give quantitative data.

PROCEDURE

Uneven inlet pressure distributions were produced by screens installed $9\frac{1}{4}$ inches upstream of the inlet instrumentation (station 2) and 17 inches upstream of the inlet guide vanes. Ram or inlet pressure was

~~CONFIDENTIAL~~

3477

CQ-1 back

based on the average of 64 total-pressure tubes behind the screens at the compressor inlet. Average inlet pressure was set to simulate complete ram pressure recovery at a flight Mach number of 0.80.

Accelerations were produced by a specially designed external fuel valve capable of producing a very rapid (0.02 sec) increase from one fuel flow to another. Sudden changes of this type are referred to as step changes. Surge lines were determined by introducing a series of steps at different initial speeds. No attempt was made to determine the values of fuel flow at surge by the usual trial and error method, since it was established during the investigation of this engine reported in reference 5 that pressure ratio at surge is not affected by the rate or size of the fuel flow change.

The exhaust nozzle was sized on the undistorted engine at a simulated altitude of 35,000 feet and a Mach number of 0.80 with open inlet guide vanes and rated engine speed to produce rated exhaust gas temperature. Nozzle area was then maintained constant. Unless otherwise specified all speed and temperature values have been corrected to standard conditions. Inlet-air temperature varied from 20 to 70° F, and the variable inlet guide vanes were set manually either open or closed.

DEFINITIONS OF DISTORTIONS

In order to provide a methodical basis for study, radial, inverse radial, and circumferential distortions were employed. Of these, typical examples were selected for discussion. The following table summarizes the distortion configurations discussed:

Distortion	Distribution	Magnitude at rated speed, percent
C-21	Circumferential (symmetrical about a compressor diam.)	21.0
C-26	Circumferential (symmetrical about a compressor diam.)	25.8
R-11	Radial (low pressure at outer annulus)	11.1
R-12	Radial (low pressure at outer annulus)	12.5
I-13	Inverse radial (low pressure at hub)	13.5
I-16	Inverse radial (low pressure at hub)	15.6

The letters in the keying system refer to the type of distortion (C, circumferential; R, radial; and I, inverse radial) and the numbers give the approximate magnitude of the distortion at rated engine speed in percent. The magnitude of distortion is defined as the maximum difference in local total pressures divided by the average total pressure at the compressor inlet $(P_{2,max} - P_{2,min})/P_{2,av}$.

3477 The circumferential distortions C-21 and C-26 have pressure profiles at the compressor inlet (symmetrical about a compressor diam.) as shown in figure 3(a).

The pressure profiles for the radial and inverse radial distortions (R-11 and R-12; I-13 and I-16) are shown in figure 3(b). The shapes of the profiles were intentionally made to differ slightly, but in general the radial distortions have a region of low pressure at the outer annulus and a region of high pressure at the hub. The opposite is true of inverse radial distortions.

The typical compressor inlet pressure variations illustrated in figure 3 show the profiles at rated engine speed. Because the distortions were produced by pressure drop across screens, the magnitude changed with engine air flow or speed. This variation is illustrated for closed inlet guide vanes in figure 4(a) and for open inlet guide vanes in figure 4(b).

RESULTS AND DISCUSSION

A study of the effects of distortion on the steady-state performance of the same engine discussed herein established that the effects of inlet distortion result from changes in compressor performance alone. In the following discussion, consideration will first be given to an examination of the underlying aerodynamic conditions in the compressor that contribute to the transient characteristics of the engine. The latter part of the discussion considers the changes in acceleration capability produced by inlet-air distortion.

Data are presented for closed and open inlet guide vane operation over the complete speed range from about 60 percent to rated speed. Although the inlet guide vane schedule will not permit operation with open inlet guide vanes at engine speeds below 7000 rpm, the compressor characteristics at lower speeds are of basic interest in compressor design.

Qualitatively, the results indicate basically similar phenomena with distorted or undistorted flow over the range of altitudes investigated. Therefore, the characteristics with no distortion are described first, followed by a discussion of the effects of distortion caused by changing these characteristics.

Compressor Characteristics

Closed inlet guide vanes. - The operational limits and steady-state line of the compressor with closed inlet guide vanes and no distortion are shown in figure 5 in terms of compressor pressure ratio and engine speed. No stall is encountered over the whole speed range of steady-state operation. At engine speeds above 5800 rpm, acceleration is limited by compressor surge, while below 5300 rpm the limit is imposed by rotating stall. Surge, and particularly rotating stall (which occurs at steady state with open inlet guide vanes), is described in detail in the next section.

Open inlet guide vanes. - With open inlet guide vanes, the operational limits of the compressor depend on the mode of operation at steady state prior to an attempted acceleration as well as the physical phenomena encountered at the limit. To provide a better physical understanding, the definition of limits is described in three steps: (1) a description of flow phenomenon at steady state, (2) a description of attempted accelerations, and (3) the definition of operational limits.

Steady-state operating line: The steady-state operating line, in terms of compressor pressure ratio and engine speed, is shown in figure 6. Shaded bars are used to represent the speed range of operation in rotating stall and tip stall (with the undistorted inlet flow). As engine speed is increased, the tip stall and rotating stall regions occur at higher engine speeds than when speed is decreased. This is a hysteresis effect, similar to that described in references 5 and 6.

To assist in understanding the nature of the stall and rotating stall, air flow fluctuations near the rotor blade tips in the first and sixth stages of the compressor are illustrated in figure 7 by representative hot-wire anemometer traces. Representations of the flow in the first stage are included in figure 7 to illustrate, by means of shaded area, the strength and extent of the regions of low flow in the annulus. The representations are constructed from hot-wire traces at several heights in the annulus, and from temperature and pressure measurements. The low flow regions are essentially the same in the sixth stage.

At high engine speeds where the compressor operates stall-free at steady state (see fig. 6) only small random irregularities of flow exist, as shown in figure 7(a). (The sixth stage trace is affected slightly by external 60-cycle disturbances.)

Figure 7(b) illustrates the flow in the speed range of rotating stall. The region of low, or stalled, flow rotates in the direction of compressor rotation at about one-half engine speed. With this engine, only one segment of rotating stall extending almost axially through the compressor is found. Generally, the stalled segment rotates at the outer

~~CONFIDENTIAL~~

wall of the annulus and covers less than half the radius. Circumferentially, from one-quarter (at higher engine speeds) to three-quarters (at lower speeds in the range of rotating stall) of the annulus may be covered by the stalled region. The example at 6000 rpm illustrated in figure 7(b) has about two-thirds of the circumference of the annulus stalled.

3477 A representation of the flow in the low, or tip stall, speed range is shown in figure 7(c). Typical of tip stall is a large, nonperiodic fluctuation of flow at the blade tips. The stalled region extends over slightly less than half the radius, but covers the whole circumference of the annulus.

The presence of tip stall and rotating stall does not necessarily prevent steady-state operation, but either tip stall or rotating stall tends to reduce performance (ref. 5), and may cause vibration and operational problems. The next few paragraphs illustrate the effects of stall on the acceleration of the engine.

Acceleration characteristics: Figure 8 illustrates typical attempted accelerations with open guide vanes from the three regions of steady-state operation with fuel steps sufficient to cause surge or stall.

An attempted acceleration from steady-state operation in the stall-free (high-speed) region leads to surge (fig. 8(a)). Surge is a violent, low-frequency (2 to 6 cps) cycling of flow and pressure throughout the compressor. If blow-out occurs during an attempted acceleration, it follows the initial breakdown of flow into surge; the limiting pressure ratio is unchanged and compressor operation follows the dashed line in figure 8(a).

An attempted acceleration from steady-state operation in tip stall results in surge-with-stall in the manner illustrated in figure 8(b). A fuel step introduced at point (a) causes a rise in compressor pressure ratio to a limit at point (b). At point (b) rotating stall is encountered, and compressor pressure ratio cannot be increased beyond the value at the inception of rotating stall. After reaching the limit, compressor pressure ratio (in the example illustrated in fig. 8(b)) decreases to surge-with-stall at point (c) after an acceleration of 450 rpm with compressor pressure ratio decreases from 2.4 to 2.25. Surge-with-stall is only slightly less violent than surge; the frequency of oscillation throughout the compressor is a little higher than with surge (5 to 12 cps). As the name implies, rotating stall is superimposed on the surge during the complete surge-with-stall cycle. The deterioration to surge-with-stall ((b) to (c)) may take place immediately or after an acceleration up to 1000 rpm with compressor pressure ratio either increasing or decreasing. A further discussion may be found in reference 5.

~~CONFIDENTIAL~~

For accelerations from tip stall, compressor performance begins to deteriorate at the inception of rotating stall. Thus, an attempted acceleration from a steady-state condition in which rotating stall is present (fig. 8(c)) results in immediate breakdown to surge-with-stall unless the acceleration is made in the most cautious manner.

Operational limits: The operational limits for open inlet guide vanes are shown for the undistorted compressor in figure 9 with the limits corresponding to each of the three regions of steady-state operation so labeled. The bars indicating the regions of rotating stall and tip stall are shown only for steady-state operation with speed increasing. (1) For excessively rapid accelerations from initial conditions at engine speeds below 5800 rpm, the compressor is limited by the occurrence of rotating stall. This limit (see fig. 8(b)) is the locus of the points labeled (b), not the point at which surge-with-stall begins. (2) For accelerations from initial speeds in the speed range of steady-state rotating stall, 5800 to 6400 rpm in figure 9, the operational limit is imposed by an immediate breakdown leading directly to surge-with-stall. (3) For attempted acceleration in the high-speed range, 6000 rpm up, where the steady-state operation is stall-free, the compressor is limited by surge.

Engine operation in any type of surge or stall is undesirable because of danger to the engine and the possibility, described later in this report, of not being able to accelerate at all.

The acceleration margin, or the difference between the steady-state line and the operational limit, is very small in the speed range of steady-state rotating stall. For this reason the inlet guide vanes of the compressor have been scheduled in the closed position in this speed range.

Effect of distortions on operational limits. - In general, the characteristics of the undistorted compressor with open guide vanes, as just described, are not qualitatively changed by the introduction of compressor inlet-air distortion. To illustrate some of the quantitative changes that take place, as well as the only significant qualitative change, figure 10 shows the steady-state line and operational limits of the compressor with radial distortion (R-12). Shown also in figure 10 is the distortion magnitude with which the characteristics were obtained.

With radial distortion the speed range of steady-state operation in rotating stall has shifted to 6550 to 7100 rpm (with no distortion, it was 5800 to 6400 rpm; in both cases with speed increasing). Also, in the range of rotating stall, at speeds higher than 6700 rpm, compressor pressure ratio decreases with increasing speed. At 7100 rpm, acceleration is limited by surge-with-stall. Although the engine will accelerate through any of the surge or stall phenomena described, in this case acceleration is impossible. Subsequent operation at higher speeds is

~~CONFIDENTIAL~~

possible if the inlet guide vanes are closed during acceleration and opened above the speed range of rotating stall.

With the exception of the region of negative slope, flow fluctuations within the distorted and undistorted compressor have the same characteristics. Representations and hot-wire anemometer traces illustrating the flow fluctuations in the region of negative slope are shown in figure 11. The severely stalled region at the hub of the sixth stage is in phase with the stalled region at the first stage; both rotate at about half engine speed. Stage performance parameters permit further study of this area of negative slope and the hub stall which is coincident with it.

Compressor Stage Performance

Compressor stage performance is discussed first in terms of the average values at any stage group in the compressor and then in terms of the local performance at the root and tip sections of the blades. The inter-stage instrumentation (fig. 2) was located axially so that the compressor could be analyzed in four groups of stages: first to fourth, fifth to seventh, eighth to tenth, and eleventh and twelfth.

Average-stage group performance. - Closed inlet guide vanes: Figure 12 shows the stage performance of the compressor with undistorted, radially, and inverse radially distorted inlet conditions for steady-state operation with closed inlet guide vanes. Flow coefficient (varies inversely as angle of attack) and pressure coefficient (a measure of adiabatic pressure rise) are used to indicate the performance of the stage groups. The derivations for the stage performance parameters may be found in references 7 and 8.

With undistorted flow (fig. 12(a)), stages one to four operated over a range of flow coefficient from 0.35 to 0.41 and a range of pressure coefficient from 0.275 to 0.12 as engine speed increased from 5000 to 8000 rpm. Flow coefficient, which varies inversely as angle of attack, increased with engine speed to about 6500 rpm and then remained almost constant at higher speeds. At high engine speeds the flow in the first stage approached the choked condition, preventing further increases of flow coefficient. The influence of the flow restriction in the inlet guide vanes is apparent in the second stage group, stages five to seven, which operated at slightly higher values of both flow and pressure coefficients than the first stage group. The third group, stages eight to ten, operated over a narrow range of both flow and pressure coefficients, while the last two stages, eleven and twelve, ranged from high values of pressure coefficient at high engine speeds to negative (turbining) values at low engine speeds.

Average stage performance with a radial distortion is shown in figure 12(b). The principal effect of lowering the pressure at the blade tips is to increase the pressure coefficient of the fifth to seventh

stages. Stage groups eight to ten and eleven and twelve showed little effect of radial distortion, but the first four stages operated at higher values of flow coefficient over most of the speed range. At 4700 rpm, stages one to four showed a reduction of pressure coefficient, possibly indicative of stalled operation, although no stalled region was detected with the hot-wire instrumentation.

The introduction of inverse radial distortion (low pressure at hub) had only small effect on the performance of the stage groups eight to ten and eleven and twelve, shown in figure 12(c). Inverse radial distortion did, though, tend to increase the pressure coefficient of the first group of stages.

Open inlet guide vanes: Figure 13 shows the stage performance with open inlet guide vanes for undistorted, radially, and inversely distorted inlet conditions. (At a given engine speed, the magnitude of the distortions is greater with open inlet guide vanes than with closed inlet guide vanes; the state of the pressure profile at the compressor inlet remains the same.) The solid points indicate the region of negative slope, as described in figure 10, and are the points nearest steady-state surge-with-stall.

Stages one to four (fig. 13(a)) operated over a wide range of flow coefficient (0.32 to 0.51) and showed large effects of rotating stall and tip stall. The middle stages, five to seven and eight to ten, operated over the narrow range of both pressure and flow coefficient typical of most multistage compressors. With open guide vanes, stages five to seven operated at lower values of pressure coefficient than stages one to four. The last stages, eleven and twelve, had a small range of angle of attack, but ranged from high values of pressure coefficient down to negative, or turbining, values at low engine speeds.

The most outstanding effect of radial distortion on stage performance (fig. 12(b)) is the marked decrease of flow coefficient in the region of negative slope indicated by solid points for all stage groups. With radial distortion, in contrast to the undistorted compressor, rotating stall occurred at lower values of pressure coefficient in stages one to four and therefore at higher engine speeds.

The inverse radial distortion (fig. 13(c)) is included to illustrate the resulting improvement in the performance of the first group of stages; it is not discussed further herein. In general, inverse radial and radial distortions can be considered to have the opposite effect on the compressor.

Span-wise stage performance. - The average values of stage performance presented in figures 12 and 13 do not indicate how the span-wise blade loading varied as radial distortions were introduced. To indicate

relative loading of the blade elements, values of equivalent pressure ratio (pressure ratio corrected for engine speed, see appendix) are presented for the blade hub and tip sections as well as for the average value over the blade span.

Closed inlet guide vanes: Figures 14 to 17 show the hub, average, and tip values of pressure ratio for the undistorted and the radially distorted compressor with closed inlet guide vanes as a function of engine speed.

Stages one to four (fig. 14) produced an equivalent pressure ratio of about 1.22 at 5000 rpm, decreasing to about 1.09 at 8000 rpm. In the undistorted compressor (fig. 14(a)), the rotor blade tips had a pressure ratio somewhat higher than the average, the roots somewhat less. With radial distortion (fig. 14(b)), the average value of equivalent pressure ratio is slightly increased over most of the speed range, and the difference between the tip and root pressure ratios is double the difference undistorted. Equivalent pressure ratio in stages five to seven (fig. 15) is slightly higher than in the first four stages, and varied from about 1.26 at 5000 to 1.2 at 8000 rpm. With either the undistorted or radially distorted compressor, the mean value of pressure ratio is higher than the value at either the hub or tip of the blades. Pressure ratio is only about 0.01 higher with radial distortion than with no distortion. Stages eight to ten (fig. 16) operate at an equivalent pressure ratio of about 1.2 over the range of engine speed from 5000 to 8000 rpm, while the last two stages (fig. 17) turbine (equivalent pressure ratio less than 1) at 5000 rpm and load up with increasing speed to a pressure ratio of 1.16 at top speed. The effect of distortion on the last two stage groups is negligible.

Open inlet guide vanes: In figures 18 to 21, showing the equivalent pressure ratios with open inlet guide vanes, the solid lines indicate steady-state operation as engine speed is increased; the dashed lines indicate loading in regions of hysteresis or regions not accessible without changing the inlet guide vanes. In the stall-free (high-speed) region, the blade tip in the first and last stage groups operates at higher pressure ratios than the blade root section (figs. 18 and 21). Radial distortion (fig. 18(b)) tends to further increase the pressure ratio at the blade tip in the first stage group, bringing it even closer to stall and causing an increase in the speed at which stall of the outer annulus occurs.

In the tip stall region, the hub of the first stage group (fig. 18) of the undistorted compressor remains loaded, while the equivalent pressure ratio at the tip is drastically reduced. Rotating stall occupies the speed range between tip stall and stall-free operation; its transitional nature is illustrated by the increase in pressure ratio as speed is increased into and through the rotating stall range.

However, with radial distortion (parts (b) of figs. 18 to 21), as speed is increased the trend toward recovery begins as rotating stall is encountered, but a breakdown in performance occurs at the hub before recovery is complete and before stall-free operation is attained. The breakdown is not severe in the first four stages (fig. 18(b)) but is drastic in the remainder of the compressor (figs. 19 to 21(b)). The most severe breakdown occurs at the hub in the eighth to tenth stages (fig. 20). The flow fluctuations at the solid points (the region of negative slope) are represented in figure 11.

It has been illustrated in the preceding discussion that radial distortion increases the equivalent pressure ratio at the tips of the blades in the early stages, and that rotating stall occurs at higher engine speeds (i.e., closer to the design speed). Also, as speed is increased through the region of rotating stall the radial distortion causes deterioration of flow at the inner annulus (at speeds where the undistorted engine would unstall and accelerate to stall-free operation). Because the engine will operate at steady state in this region of deterioration, it has been possible to study the effects of overloading the stalled compressor on internal aerodynamics. Finally, because the compressor operates in a similar region during accelerations, it is possible to hypothesize that the reduction of performance preceding surge-with-stall (see fig. 8) is caused by a shifting of rotating stall from the outer annulus to the hub in the middle stages. The effects of various aerodynamic limitations on the acceleration characteristics of the engine are discussed in the following section in terms of acceleration margin.

Acceleration Margin

Acceleration margin is herein defined as the difference between the steady-state pressure ratio and the pressure ratio at the compressor operational limit. Acceleration margin is, therefore, an indication of the increases in pressure ratio possible before operational problems are encountered; it is an indication of the maximum possible rate of acceleration.

Effects of circumferential distortion. - Closed inlet guide vanes: The effects of circumferential distortion on acceleration margin with closed inlet guide vanes are shown in figure 22 as a function of the magnitude of distortion. The solid lines indicate that surge imposed the operational limit of the compressor, and the dashed lines indicate that rotating stall formed the operational limit.

For engine speeds below 6000 rpm, rotating stall formed the operational limit of the compressor. At 5600 rpm with a distortion of about 10 percent, acceleration margin was reduced to about 15 percent of the undistorted value.

For engine speeds above 6000 rpm, surge formed the operational limit of the compressor. In the speed range from 6200 to 6800 rpm, distortions to 17 percent reduced margin to 35 percent, but at higher engine speeds than 6800 rpm, the reduction associated with distortions ranging up to 24 percent was as high as 85 percent. It should be noted that the inlet guide vanes are not scheduled in the closed position at high speeds.

Open inlet guide vanes: The following discussion of the effects of distortion on acceleration margin with open inlet guide vanes considers only the speed range of stall-free operation. Since the inlet guide vanes were not scheduled open at speeds below 7000 to 7300 rpm, the practical range of interest is covered.

The acceleration margin for open inlet guide vane operation at various engine speeds above 6200 rpm is shown in figure 23 to indicate the changes in margin caused by symmetrical circumferential distortions. At engine speeds of 7200 rpm and above, distortions of 20 to 26 percent resulted in about 50 percent reductions in acceleration margin. At lower engine speeds the reduction was less, but was associated with distortion magnitudes ranging to only 20 percent. In subsonic duct installations, circumferential distributions of 10 to 15 percent might be expected; in this range of distortion magnitudes, acceleration margin was reduced by only 20 percent.

The compressor pressure ratio based on the lowest local compressor inlet pressure is shown in figure 24 with the undistorted surge pressure ratio and the surge pressure ratio with circumferentially distorted compressor based on average inlet pressure. (The pressure profiles at the compressor discharge are essentially flat.) The distorted pressure ratio based on minimum inlet pressure was approximately the same as the undistorted surge pressure ratio over most of the speed range. Thus, during an acceleration, the compressor surged when any axial segment reached approximately the surge pressure ratio of the undistorted compressor. This approximation is good only with open inlet guide vanes and circumferential distortion.

Effects of radial and inverse radial distortions. - To more fully illustrate the effects of both radial and inverse radial distortions, acceleration margin is presented as a function of $\frac{P_{\text{hub}} - P_{\text{tip}}}{P_{\text{av}}}$, causing radial distortions to appear as positive values and inverse radial distortions to appear as negative values of distortion.

Closed inlet guide vanes: The effects of radial and inverse radial distortions on acceleration margin are shown in figure 25 for closed inlet guide vane operation. The distortions ranged from 8 percent in the radial direction to 10 percent (-10 percent) in the inverse radial

direction. For engine speeds above 6400 rpm, either radial or inverse radial distortion caused reductions in acceleration margin up to 25 percent. For speeds less than 6400 rpm, radial distortions reduced acceleration margin; inverse radial distortion had little effect.

Open inlet guide vanes: The effects of radial and inverse radial distortions on acceleration margin are shown in figure 26 for open inlet guide vane operation at simulated altitudes of 15,000, 35,000, and 50,000 feet.

At 15,000 feet (fig. 26(a)) the acceleration margin for engine speeds of 7000 rpm, or higher, was reduced slightly by either radial or inverse radial distortion. For example, at rated speed a radial distortion of 11 percent resulted in a 20 percent reduction in acceleration margin, while an inverse radial distortion of 17 percent resulted in losses of acceleration capabilities of 15 percent. At engine speeds of less than 7000 rpm, radial distortion caused reduction in margin, but inverse radial distortion improved the operational characteristics of the compressor. Thus, at 6000 rpm an inverse distribution of 5 percent resulted in an increase of 25 percent in acceleration margin.

At a simulated altitude of 35,000 feet, the effects of radial and inverse radial distortion on margin were similar to (but slightly greater than) those at 15,000 feet, and are illustrated in figure 26(b). Serious reductions of margin, up to 75 percent at 6600 rpm, resulted in the speed range from 6200 to 7000 rpm with radial distortions of only 6 to 8 percent. From 7200 to 7600 rpm, the effects of radial distortion were small, but at speeds above 7800 rpm, distortions of less than 13 percent caused reductions in acceleration margin up to 50 percent.

A further increase of altitude to 50,000 feet (fig. 26(c)) resulted in large reductions of margin at high engine speeds. At rated speed (7950 rpm) a radial distortion of 12 percent and even an inverse radial distortion of 16 percent caused losses of 65 and 50 percent. The general trend, such as the increase in margin with inverse distortion at speeds below 6800 rpm, was the same as at lower altitudes.

In general, the distortions illustrated in figure 26 are less than half the magnitude of those illustrated in figure 23 with circumferential distributions. The radial distortion, therefore, is far more serious than the circumferential in its effects on open inlet guide vane compressor operational limits. Because distortions in inlet duct installations often have circumferential and radial distributions of similar magnitude (possibly 10 to 15 percent), radial distortions greater than those investigated may be encountered. It has been shown that radial distortion increased the speed range of rotating stall and that the distortions investigated were large enough to prevent acceleration out of the rotating stall region.

Figures 23 and 26 show only the changes in acceleration margin if stall-free operation is previously attained. In the range of this investigation, with the variable inlet guide vanes scheduled to open only above the speed range of rotating stall, operation is not prevented. The distortions investigated in this region (7000 to 7300 rpm) though, did not exceed 8 percent (fig. 10). With greater radial distortions at these speeds the region of rotating stall may extend into the speed range of operation with open inlet guide vanes. If so, acceleration will not be possible, even if surge-with-stall is an acceptable mode of operation.

Effects of mixed distortions on acceleration margin. - In actual duct installations, the distortions at the compressor inlet normally consist of various combinations of radial, inverse radial, and circumferential variations of pressure. Investigation of examples of mixed distortion, as well as investigation of the basic component gradations (as presented herein) indicate that the compressor was far more sensitive to radial distortion than to other distributions. Thus, mixed distortions resulted in effects similar to those of the comparable radial component alone, and are therefore not presented individually.

CONCLUDING REMARKS

Distortions in inlet-air pressure distributions had large effects on the transient characteristics of a turbojet engine equipped with variable compressor inlet guide vanes.

With closed inlet guide vanes, the compressor was not appreciably sensitive to inlet pressure reductions at either the root or tip of the rotor blade. Radial distortions of 8 percent caused reductions in acceleration margin at high engine speeds. However, in the engine speed range where the inlet guide vanes are scheduled in the closed position, reductions not exceeding 15 percent were caused by distortions to 4 percent. Circumferential distributions had a more serious effect, particularly at low (55 to 65 percent) engine speeds where the compressor operational limit is imposed by rotating stall; acceleration margin was reduced 85 percent by distortions of about 10 percent.

With open inlet guide vanes, the compressor was very sensitive to reductions in inlet pressure at the rotor blade tip. As a result, acceleration margin in the speed range in which the inlet guide vanes were scheduled open was reduced 15, 50, and 70 percent at simulated altitudes of 15,000, 35,000, and 50,000 feet, respectively, by radial distortions of 12 percent. With the undistorted compressor, the speed range of rotating stall was well below the speed at which the inlet guide vanes open. A radial distortion of 8 percent increased the speed range 700 rpm. Since radial distributions of 10 to 15 percent may be expected in

~~CONFIDENTIAL~~

an inlet duct installation, it is possible that rotating stall will occur in the range of open inlet guide vane engine operation. With radial distortion, an acceleration limit prevents increasing speed out of the range of rotating stall and would, if the inlet guide vanes were open, prevent engine acceleration completely.

Reductions of inlet pressure at the root of the rotor blade, by inverse radial distortions, slightly improved acceleration margin at medium engine speeds with open inlet guide vanes. At high engine speeds, though, reductions in acceleration margin resulted. At a simulated altitude of 50,000 feet, an inverse distortion of 16 percent reduced acceleration 50 percent.

Circumferential distortions as great as 25.8 percent were investigated with open inlet guide vanes. Circumferential distributions of 10 to 15 percent may be expected in an installation; in this range of distortion acceleration margin is reduced less than 20 percent. The engine was found to surge whenever the pressure ratio of any local segment reached the approximate pressure ratio for surge with no distortion.

Since the compressor is so much more sensitive to low pressure at the blade tips than to any other distribution, the effects of mixed distortions on open inlet guide vane operation are similar to the radial component alone.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 9, 1954

~~CONFIDENTIAL~~

3477

APPENDIX - SYMBOLS

The following symbols are used in this report:

A	area, sq ft
c_p	specific heat at constant pressure, Btu/lb/°F
g	acceleration due to gravity, 32.17 ft/sec ²
J	mechanical equivalent of heat, 778.3 ft-lb/Btu
N	engine speed, rpm
P	total pressure, lb/sq ft
R	gas constant, ft-lb/lb °F
r	radius, ft
T	stagnation temperature, °R
V_a	axial velocity, ft/sec
W	weight-flow rate, lb/sec
γ	ratio of specific heats, 1.40
θ	ratio of temperature to standard temperature
ρ	density, slugs/ft ³
ρV	instantaneous local flow rate, lb/(sec)(sq ft), used in connection with hot-wire anemometer signals

ψ pressure coefficient,
$$\frac{gJc_p T_i \left[\left(\frac{P_o}{P_i} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]}{\left(\frac{2\pi r}{60} \right)^2 N^2}$$

ϕ flow coefficient,
$$\frac{60V_a}{2\pi rN} = \left[\frac{W}{N} \right] \left[\frac{T_i}{P_i} \right] \left[\frac{60R}{2\pi rA} \right]$$

$(P_o/P_i)_e$ equivalent pressure ratio,

$$\left\{ 1 + \frac{T_{1d}}{T_{1d}} \left(\frac{N_d}{N} \right)^2 \left[\left(\frac{P_o}{P_i} \right)^{\frac{r-1}{r}} - 1 \right] \right\}^{\frac{r}{r-1}}$$

Subscripts:

av	arithmetic average value
d	value at rated conditions
e	equivalent, indicates that parameter to which it is affixed has been corrected for speed
hub	value at root section of rotor blade
i	inlet to stage group
max	maximum local value
min	minimum local value
o	outlet of stage group
tip	value at tip section of rotor blade
2	compressor inlet
3	compressor discharge

REFERENCES

1. Walker, Curtis L., Sivo, Joseph N., and Jansen, Emmert T.: Effect of Unequal Air-Flow Distribution from Twin Inlet Ducts on Performance of an Axial-Flow Turbojet Engine. NACA RM E54E13, 1954.
2. Conrad, E. William, and Sobolewski, Adam E.: Investigation of Effects of Inlet-Air Velocity Distortion on Performance of Turbojet Engine. NACA RM E50G11, 1950.
3. Wallner, Lewis E., Conrad, E. William, and Prince, William R.: Effect of Uneven Air-Flow Distribution to the Twin Inlets of an Axial-Flow Turbojet Engine. NACA RM E52K06, 1953.

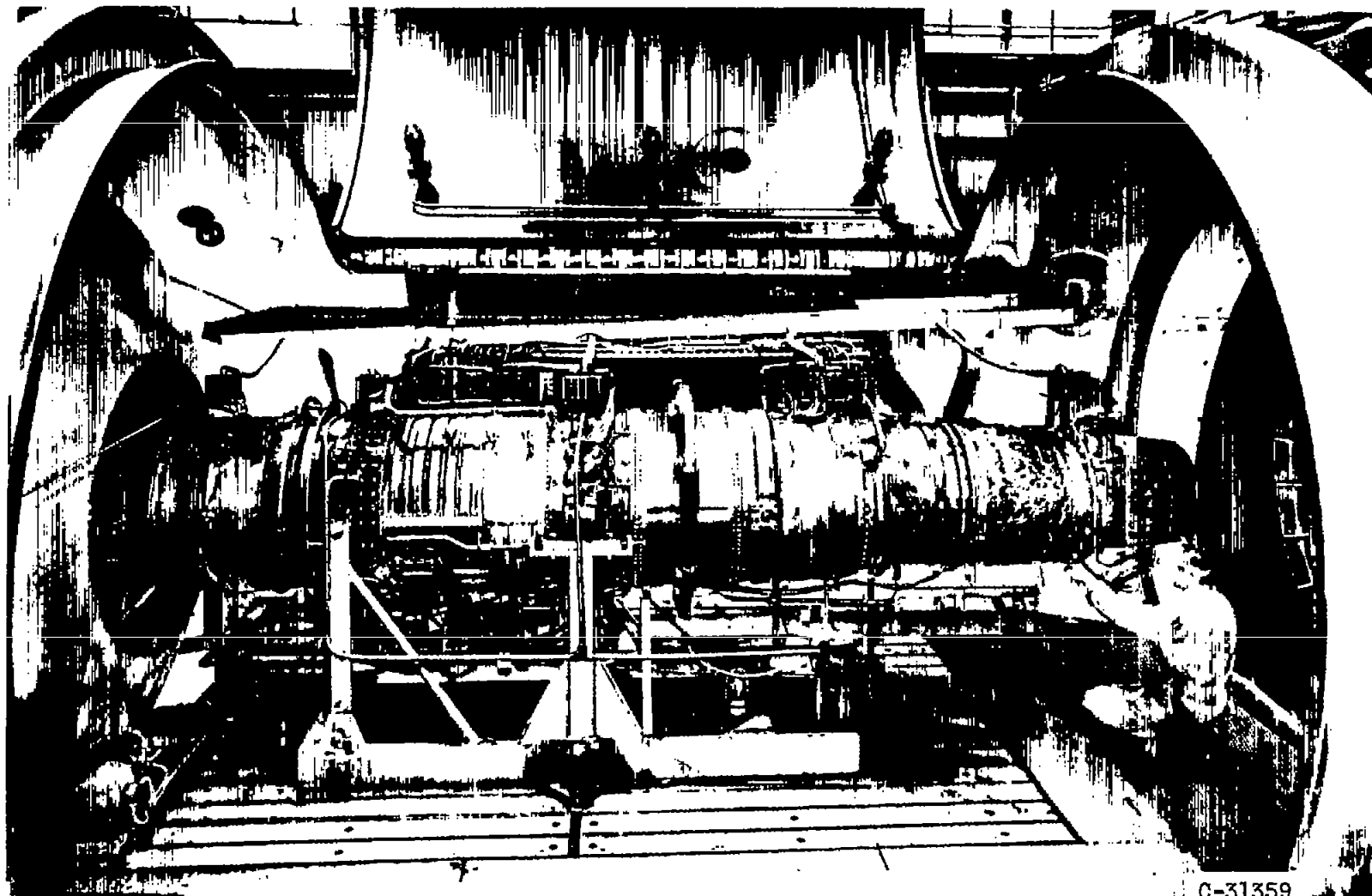
4. Kaufman, Harold R., and Dobson, Wilbur F.: Performance of YJ73-GE-3 Turbojet Engine in Altitude Test Chamber. NACA RM E54F22, 1954.
5. Wallner, Lewis E., and Lubick, Robert J.: Steady-State and Surge Characteristics of a Compressor Equipped with Variable Inlet Guide Vanes Operating in a Turbojet Engine. NACA RM E54I28, 1954.
6. Benser, William A.: Analysis of Part-Speed Operation for High-Pressure-Ratio Multistage Axial-Flow Compressors. NACA RM E53I15, 1953.
7. Medeiros, Arthur A., Benser, William A., and Hatch, James E.: Analysis of Off-Design Performance of a 16-Stage Axial-Flow Compressor with Various Blade Modifications. NACA RM E52I03, 1953.
8. Huppert, Merle C.: Preliminary Investigation of Flow Fluctuations During Surge and Blade Row Stall in Axial-Flow Compressors. NACA RM E52E28, 1952.

3477

CQ-3 back

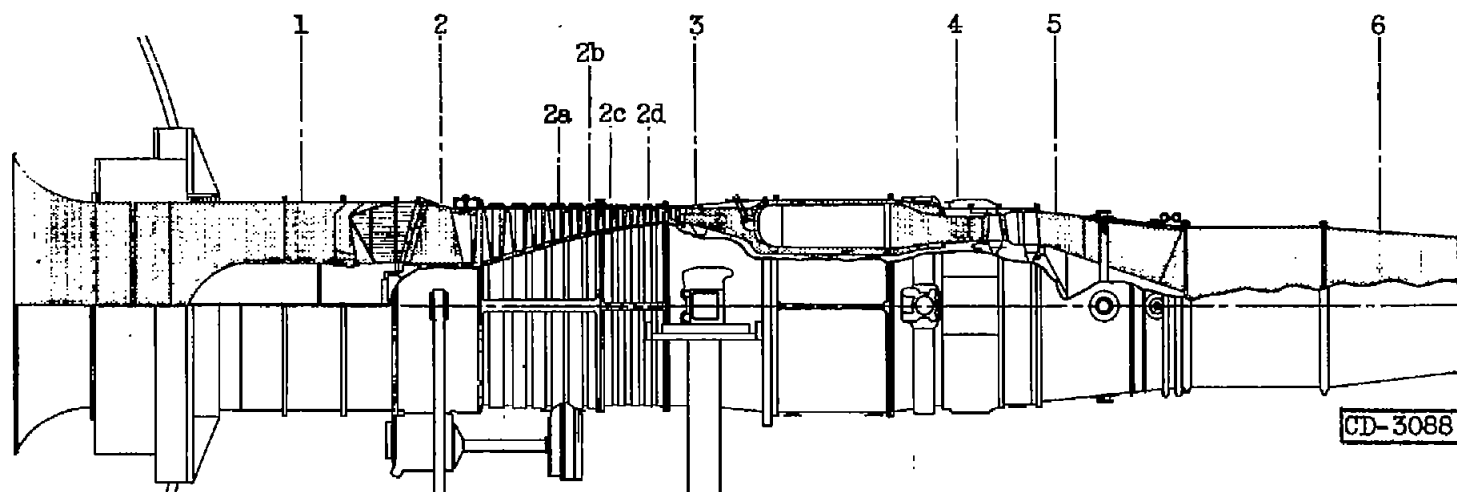
TABLE I. - LOCATION AND TYPE OF TRANSIENT SENSING DEVICES

Station	Measured quantity	Steady state		Transient		Frequency range of flat response
		Type	Number	Type	Number	
2	Compressor inlet total pressure	Bourdon-type gages	2	Aneroid-type pressure sensors with strain-gage element	2	Zero to 10 cps sea-level static
3	Compressor outlet total pressure	Bourdon-type gage	1	Aneroid-type pressure sensors with strain-gage element	1	Zero to 10 cps sea-level static
6	Exhaust gas temperature	Parallel thermocouples connected to self-balancing potentiometer recorder	5	Paralled 20-gage chromel-alumel butt-welded thermocouples, with electric network to compensate for thermocouple lag	6	Zero to 30 cps
-	Engine speed	Chronometric tachometer	1	Magnetic pickup with output frequency proportional to engine speed	1	Zero to 5 cps
-	Fuel flow	Calibrated rotameters	2	Aneroid-type pressure sensors with strain-gage element connected to measure pressure drop across variable orifice in fuel line	1	Undetermined



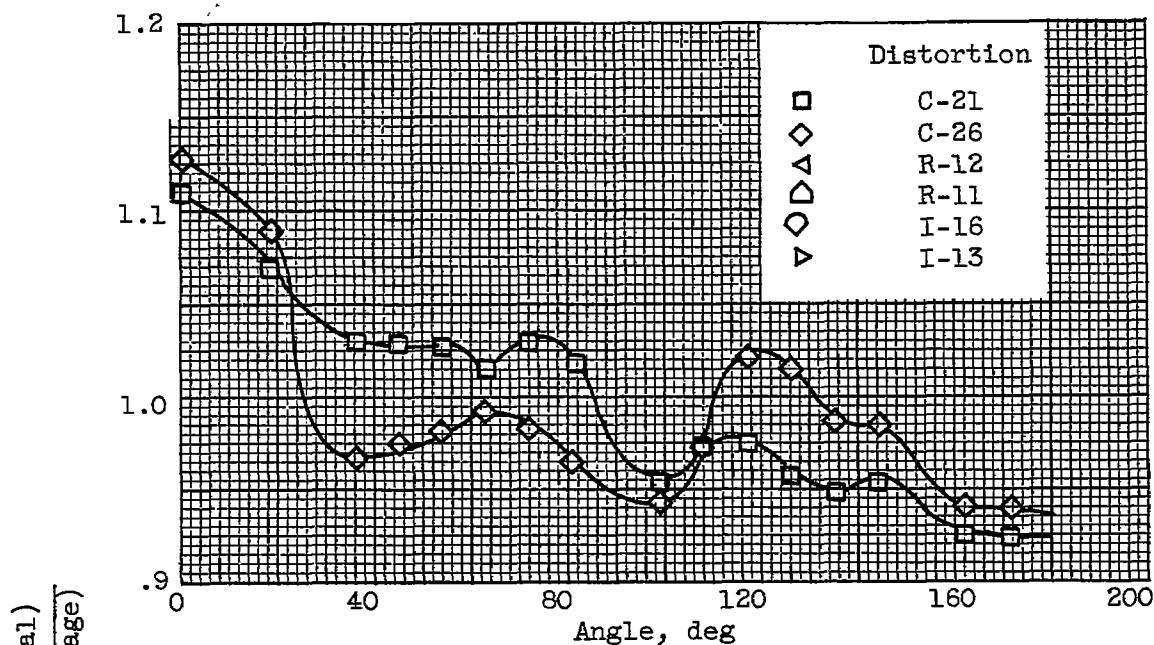
C-31359

Figure 1. - Installation of experimental turbojet engine in altitude chamber.

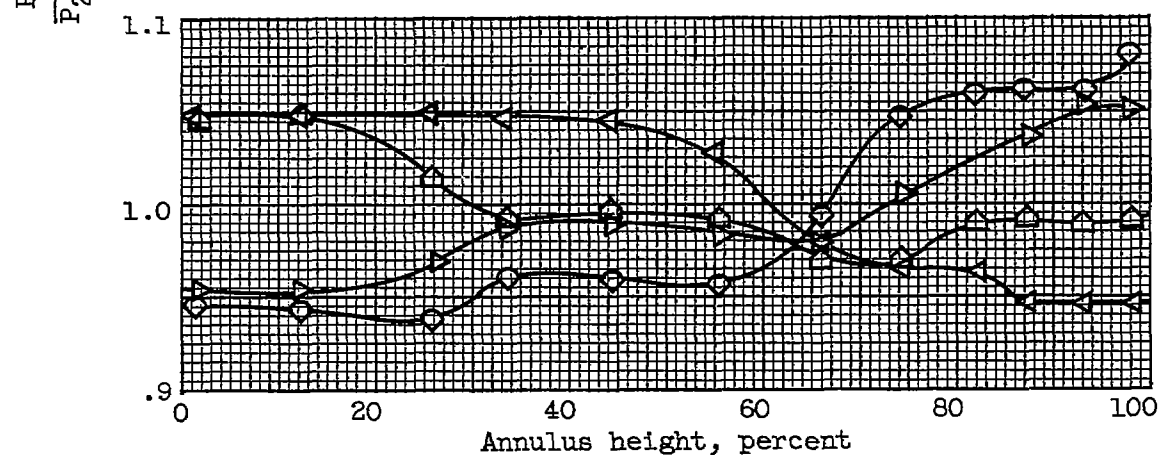


Station	Location	Total-pressure tubes	Static pressure tubes	Wall-static orifices pressure	Thermo-couples
1	Engine inlet	-	-	-	16
2	Compressor inlet	64	-	-	-
2a	Compressor 4th stage	5	-	1	5
2b	6th stage	-	-	1	-
2c	7th stage	5	-	-	5
2d	10th stage	5	-	-	5
3	Compressor outlet	59	-	-	49
4	Turbine inlet	9	-	-	-
5	Turbine outlet	24	-	-	20
6	Exhaust nozzle	14	-	2	20

Figure 2. - Side view of turbojet engine installation showing stations at which steady-state instrumentation was installed.

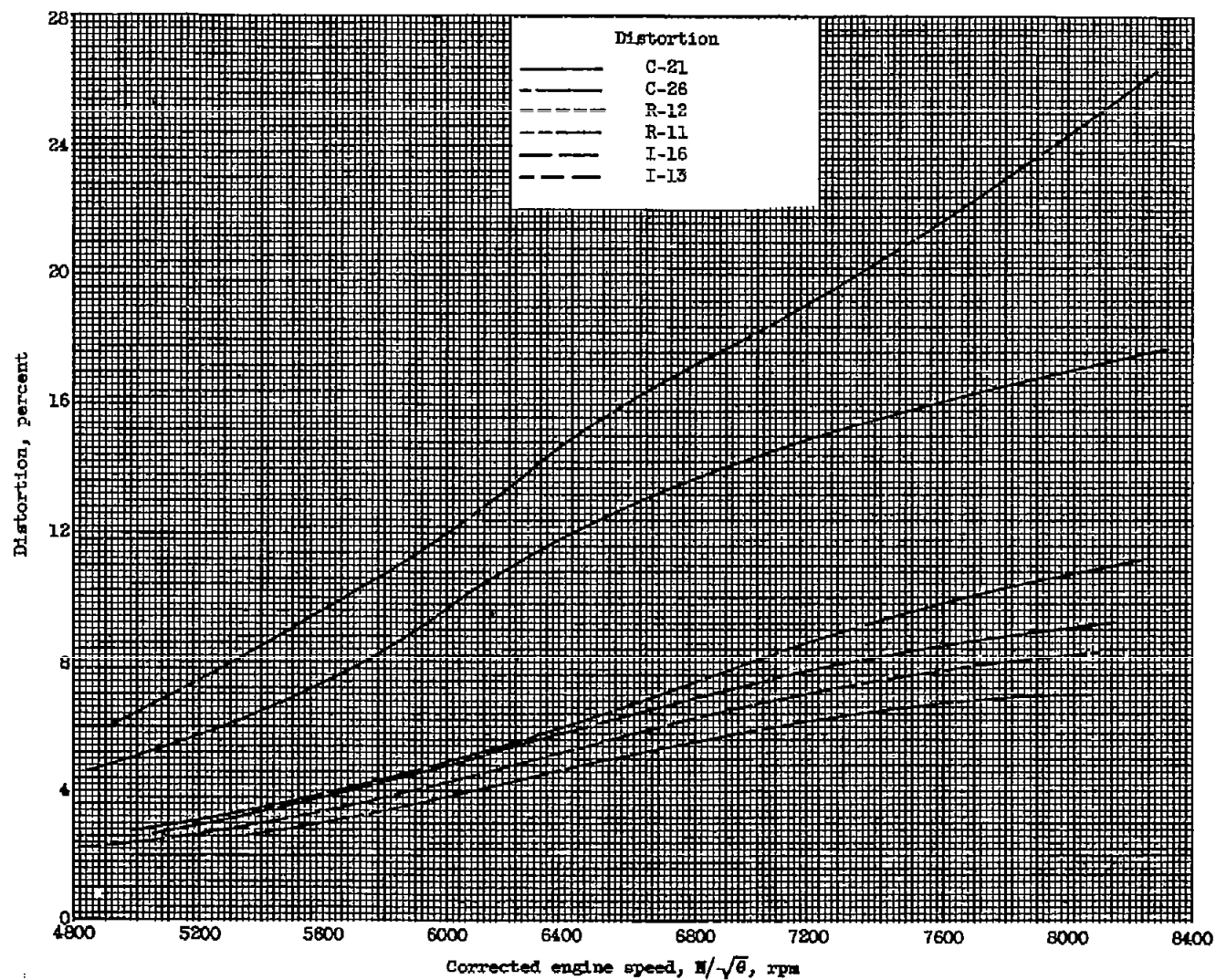


(a) Circumferential distributions.



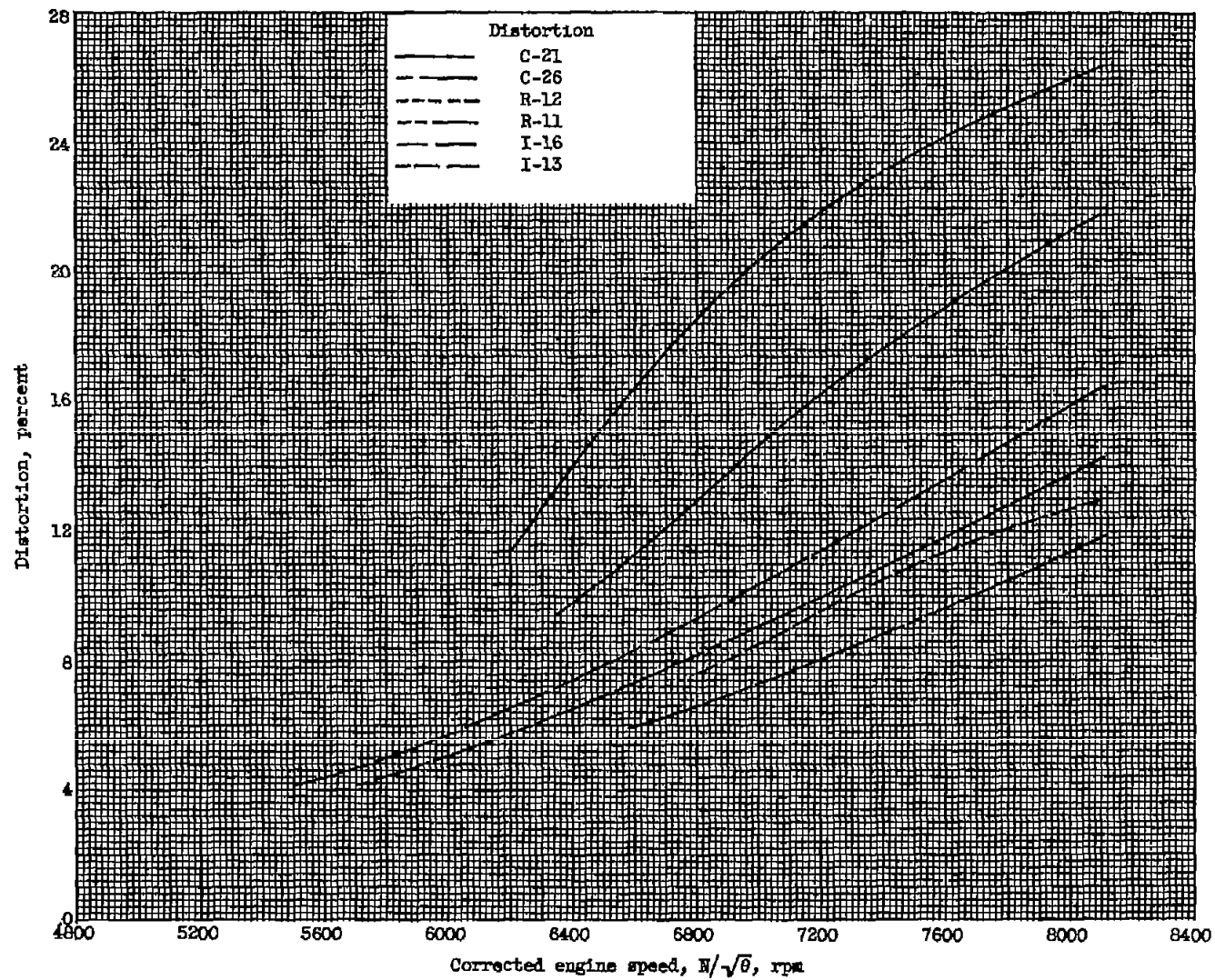
(b) Radial and inverse radial distributions.

Figure 3. - Pressure profiles at compressor inlet. Inlet guide vanes open; rated engine speed, 35,000 feet.



(a) Inlet guide vanes closed.

Figure 4. - Variation of distortion with engine speed. Simulated altitude, 35,000 feet.



(b) Inlet guide vanes open..

Figure 4. - Concluded. Variation of distortion with engine speed. Simulated altitude, 35,000 feet.

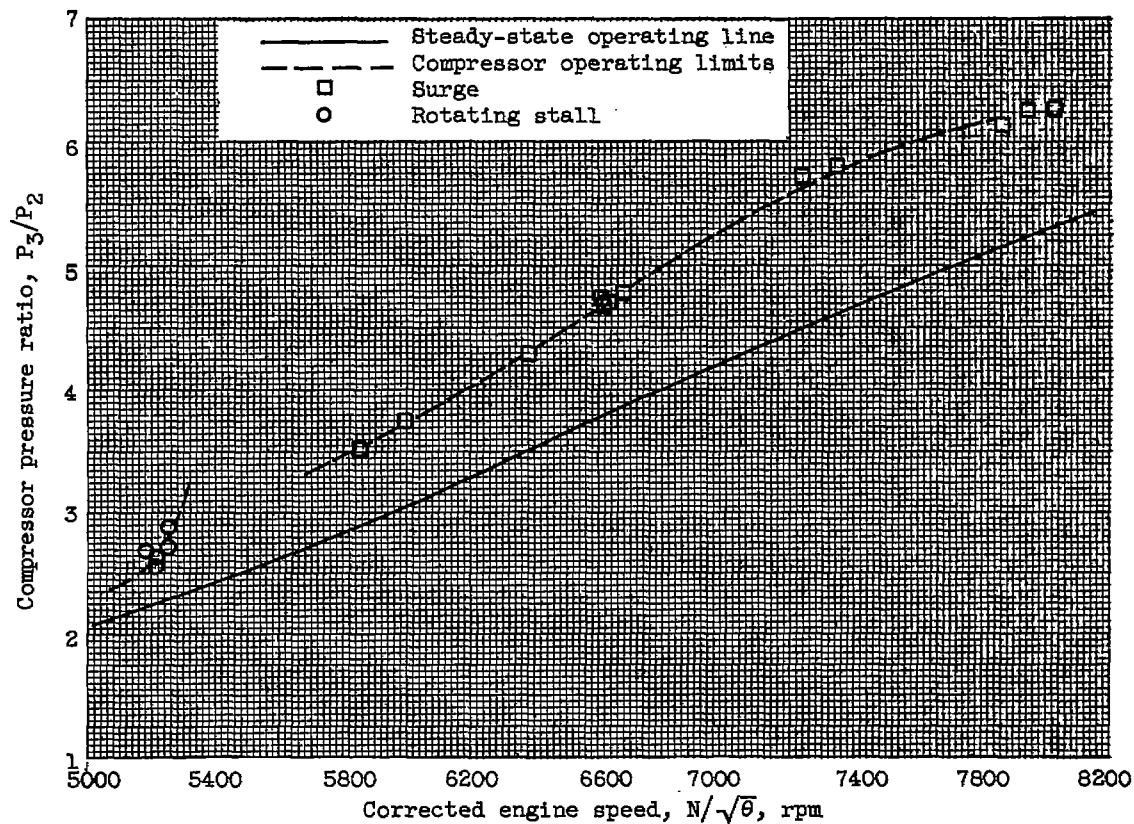


Figure 5. - Compressor operational limits. Undistorted; closed inlet guide vanes; altitude, 35,000 feet.

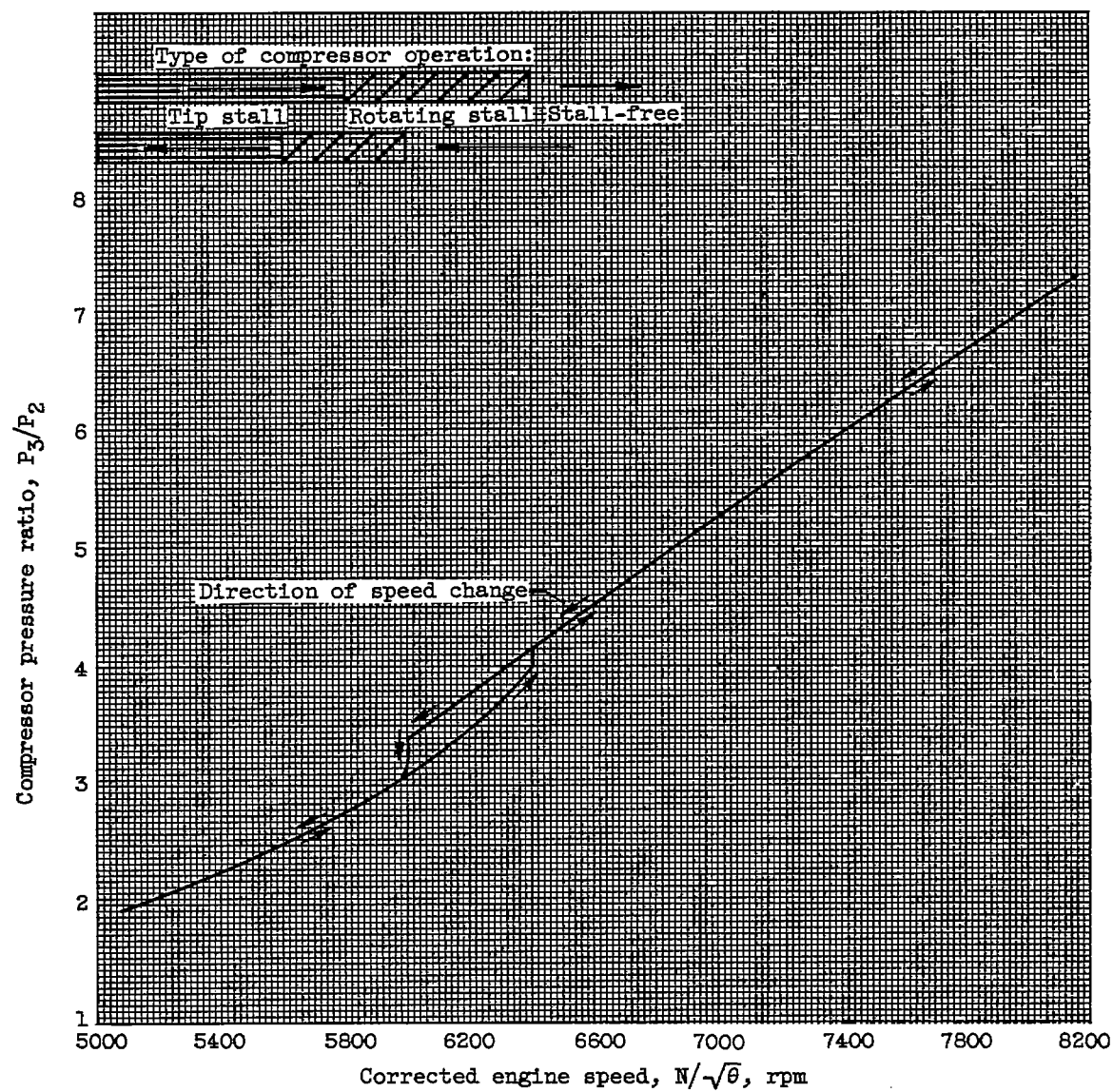
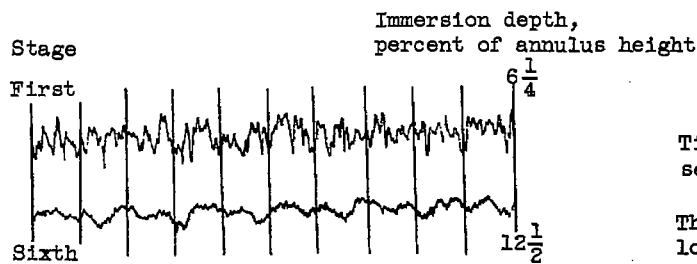


Figure 6. - Steady-state operating line. Altitude, 35,000 feet; undistorted; open inlet guide vanes.

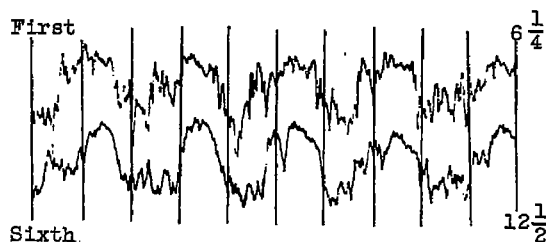
~~CONFIDENTIAL~~

(a) Stall-free operation, 7000 rpm.

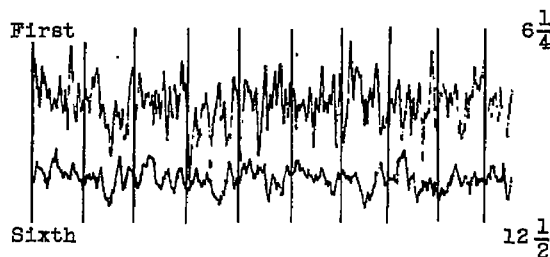
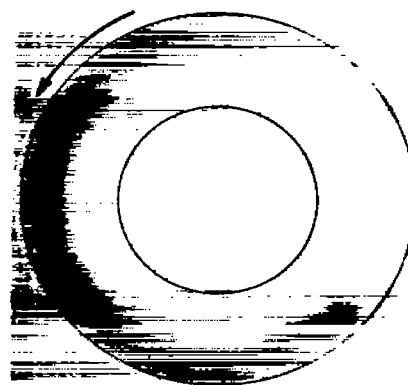
Timing lines indicate .01
sec, increasing to right

The signal, instantaneous
local flow rate, $f(\rho V)$,
increases upwards.

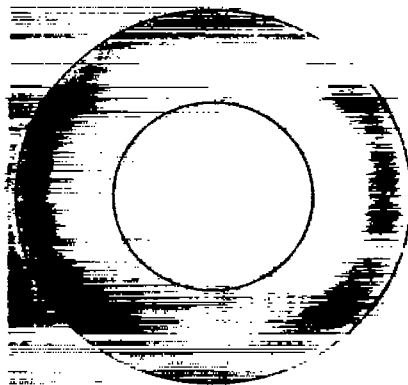
Shaded areas represent
regions of low flow



(b) Rotating stall, 6000 rpm.



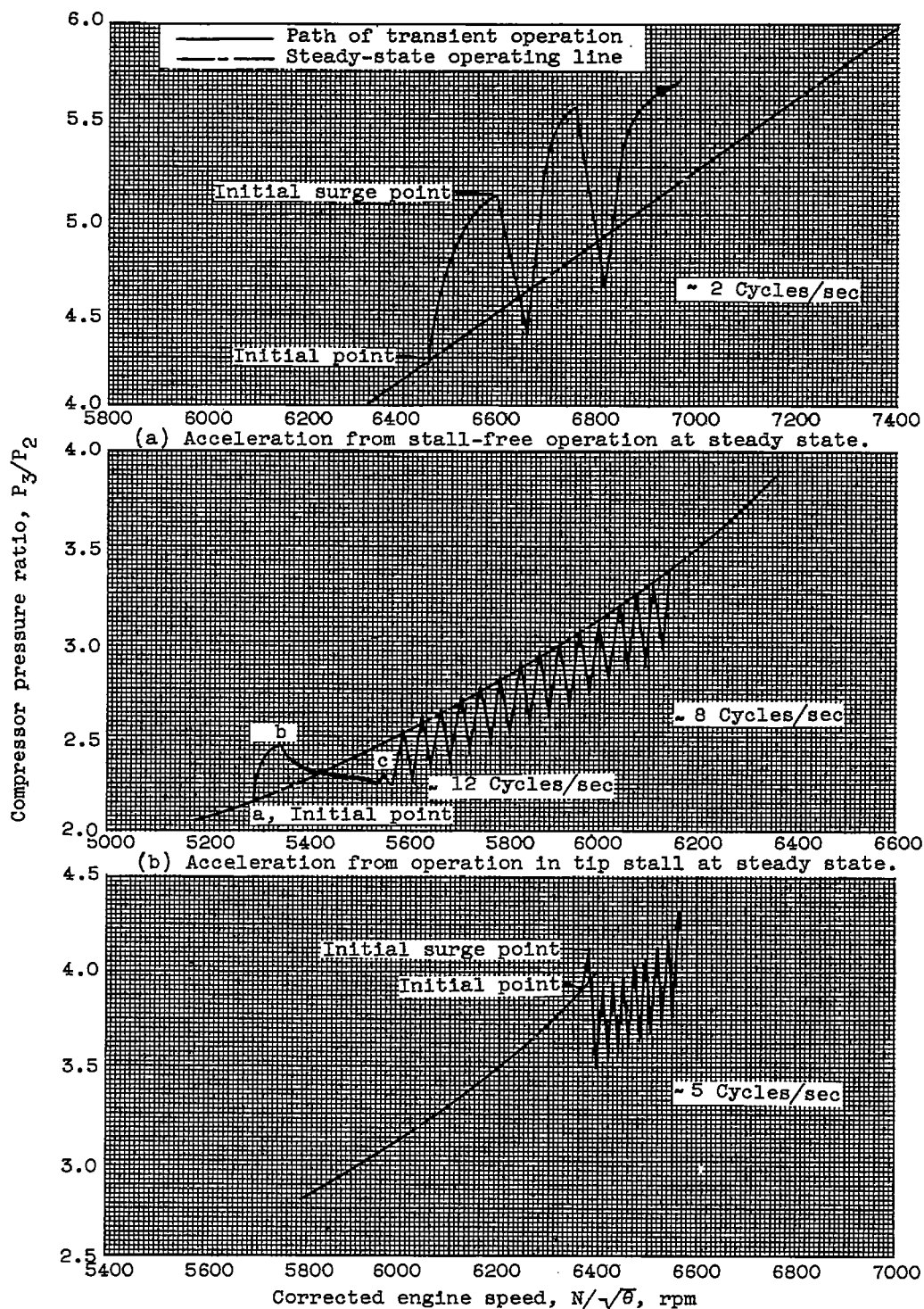
(c) Tip stall, 5400 rpm.



CD-4108

Figure 7. - Typical hot-wire anemometer traces, with representations of the flow fluctuations at compressor first and sixth stages. Undistorted; altitude, 35,000 feet; open inlet guide vanes.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

(c) Acceleration from operation in rotating stall at steady state.

Figure 8. - Typical attempted accelerations. Undistorted; inlet guide vanes open; altitude, 35,000 feet.

~~CONFIDENTIAL~~

~~CONFIDENTIAL~~

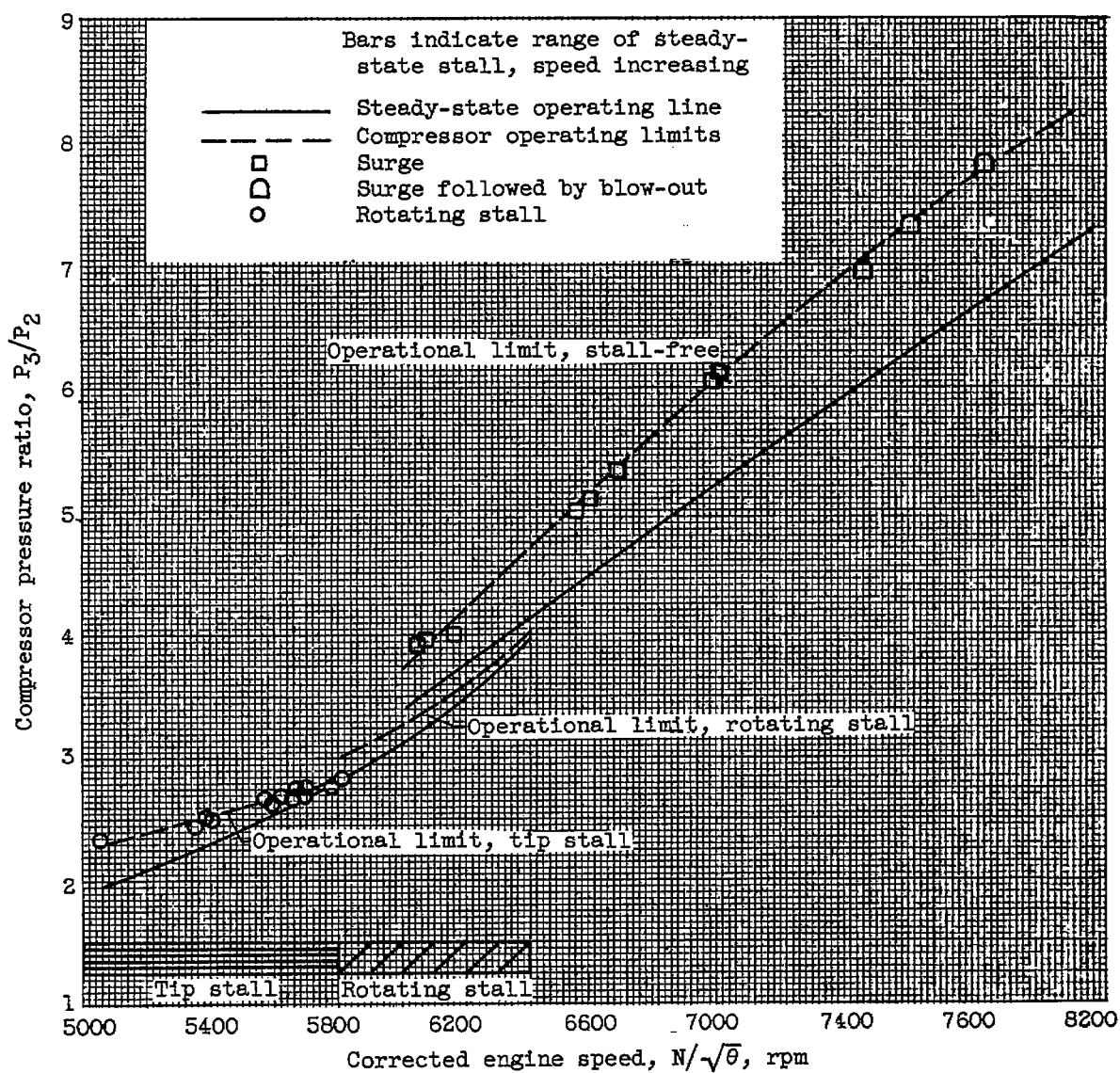


Figure 9. - Compressor operational limits. Undistorted; open inlet guide vanes; altitude, 35,000 feet.

~~CONFIDENTIAL~~

3477

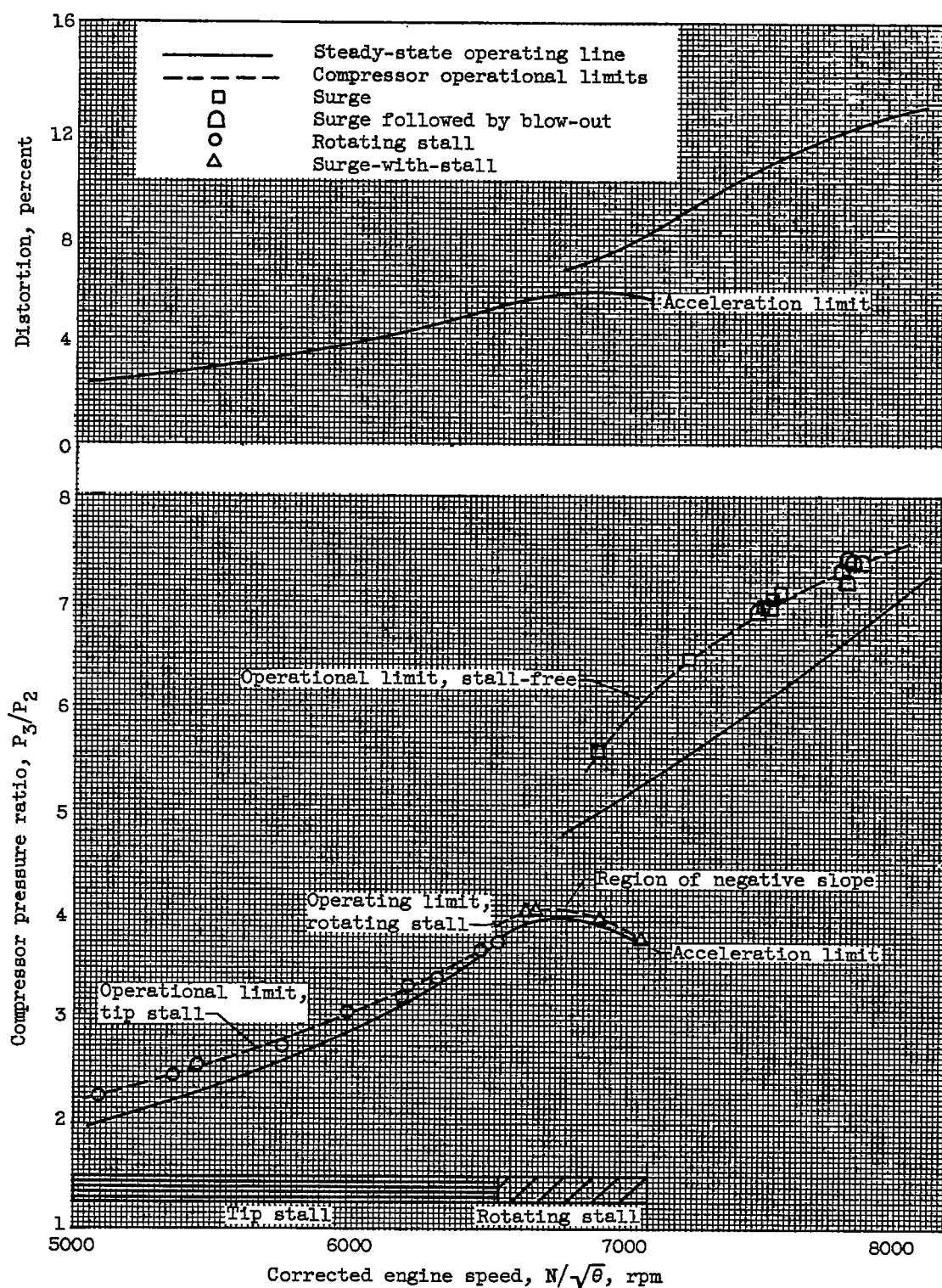


Figure 10. - Compressor operational limits. Radial distortion; open inlet guide vanes; altitude, 35,000 feet.

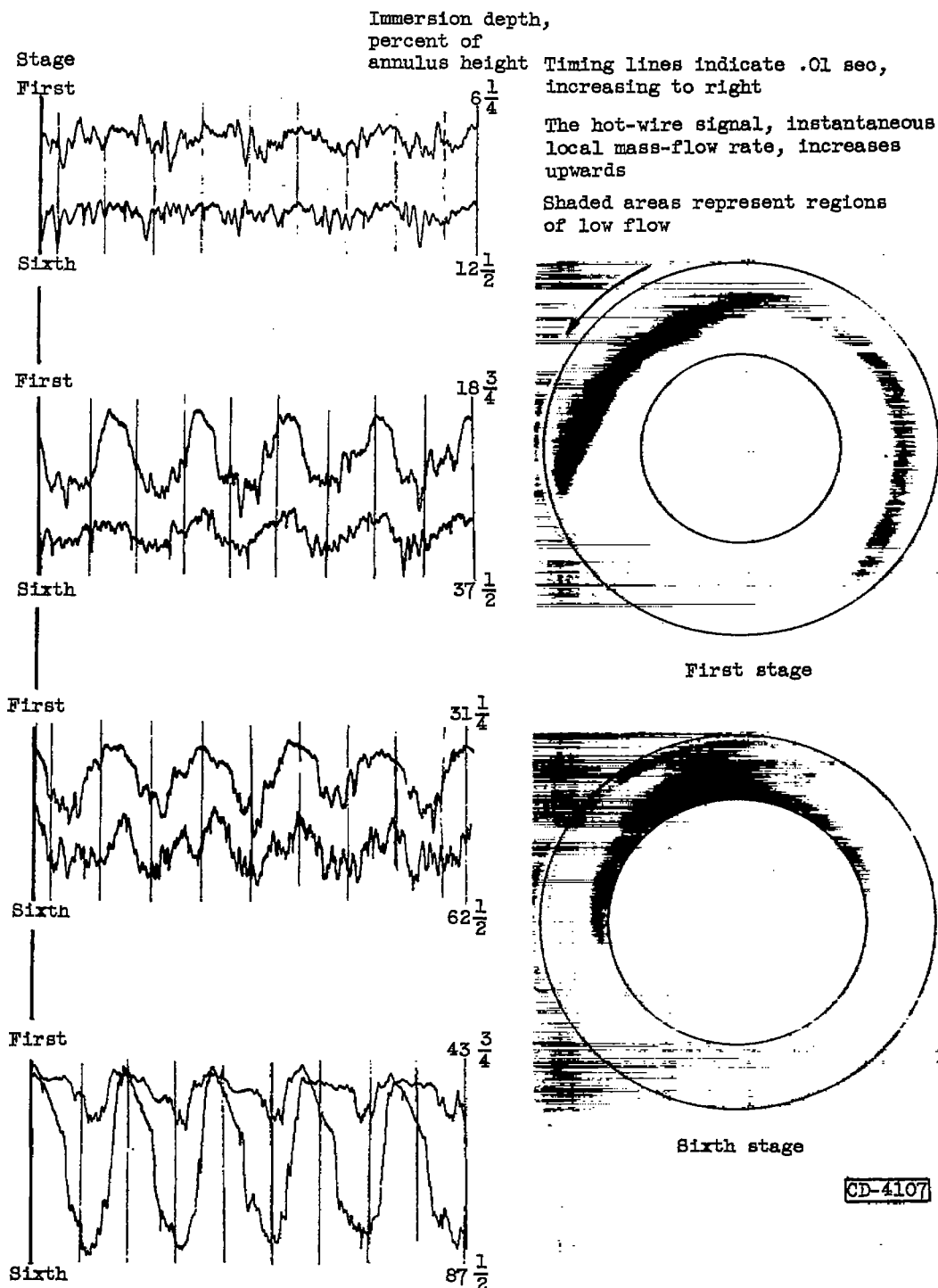


Figure 11. - Anemometer traces and representations of flow fluctuations at first and sixth stages. Operation with radial distortion just prior to steady-state surge; altitude, 35,000 feet; open inlet guide vanes.

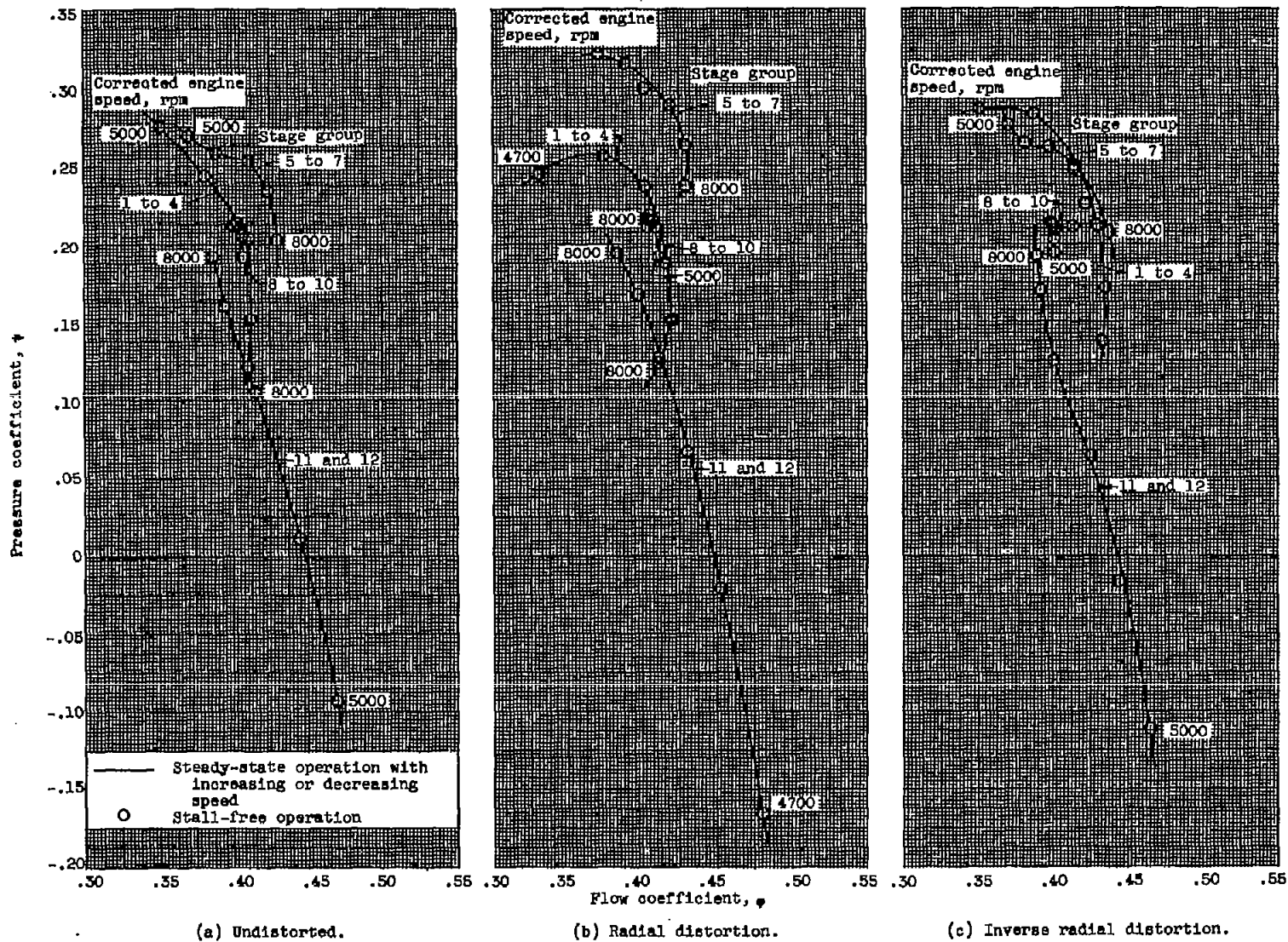
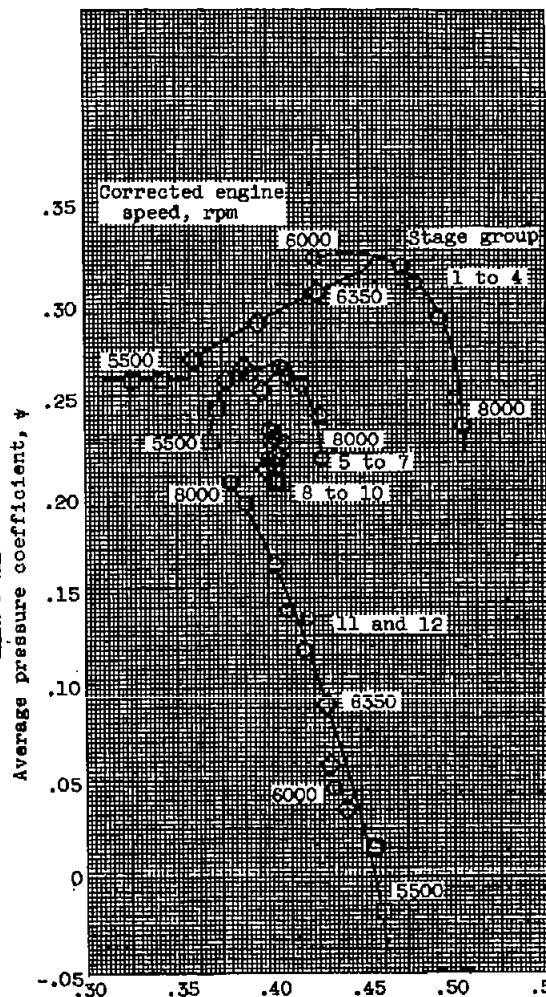
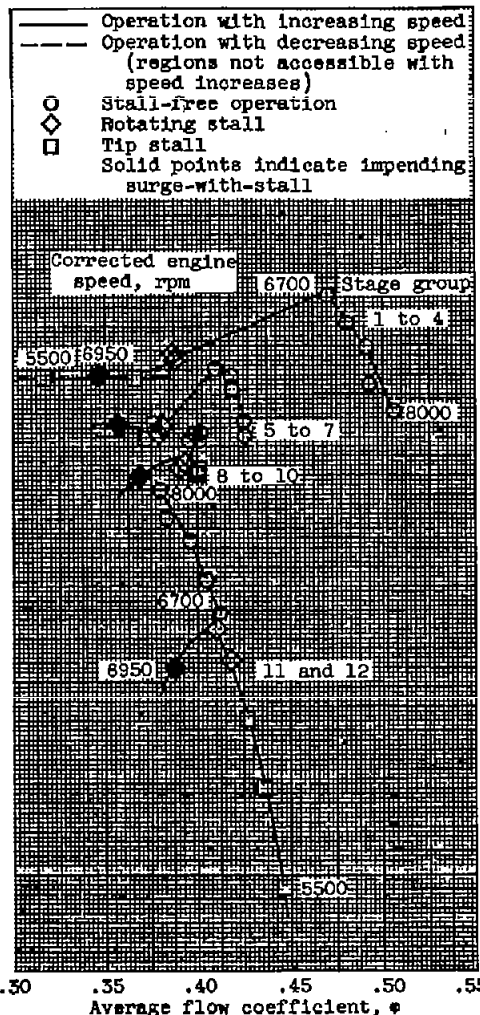


Figure 12. - Effect of radial and inverse radial distortion on average stage performance. Closed inlet guide vanes.

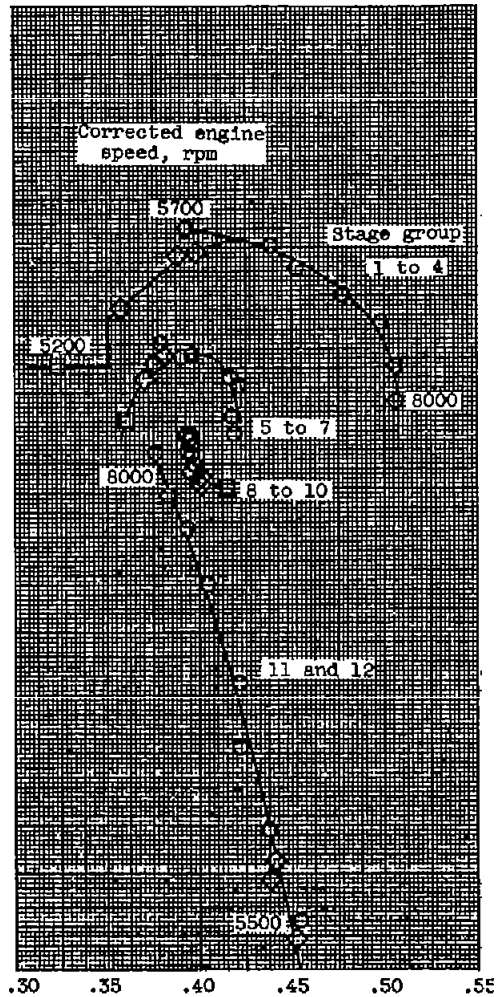
CONFIDENTIAL



(a) Undistorted.



(b) Radial distortion.



(c) Radial inverse distortion.

Figure 13. - Effect of radial and inverse radial distortion on average stage performance. Altitude, 35,000 feet; Mach number, 0.80; open inlet guide vanes.

CONFIDENTIAL

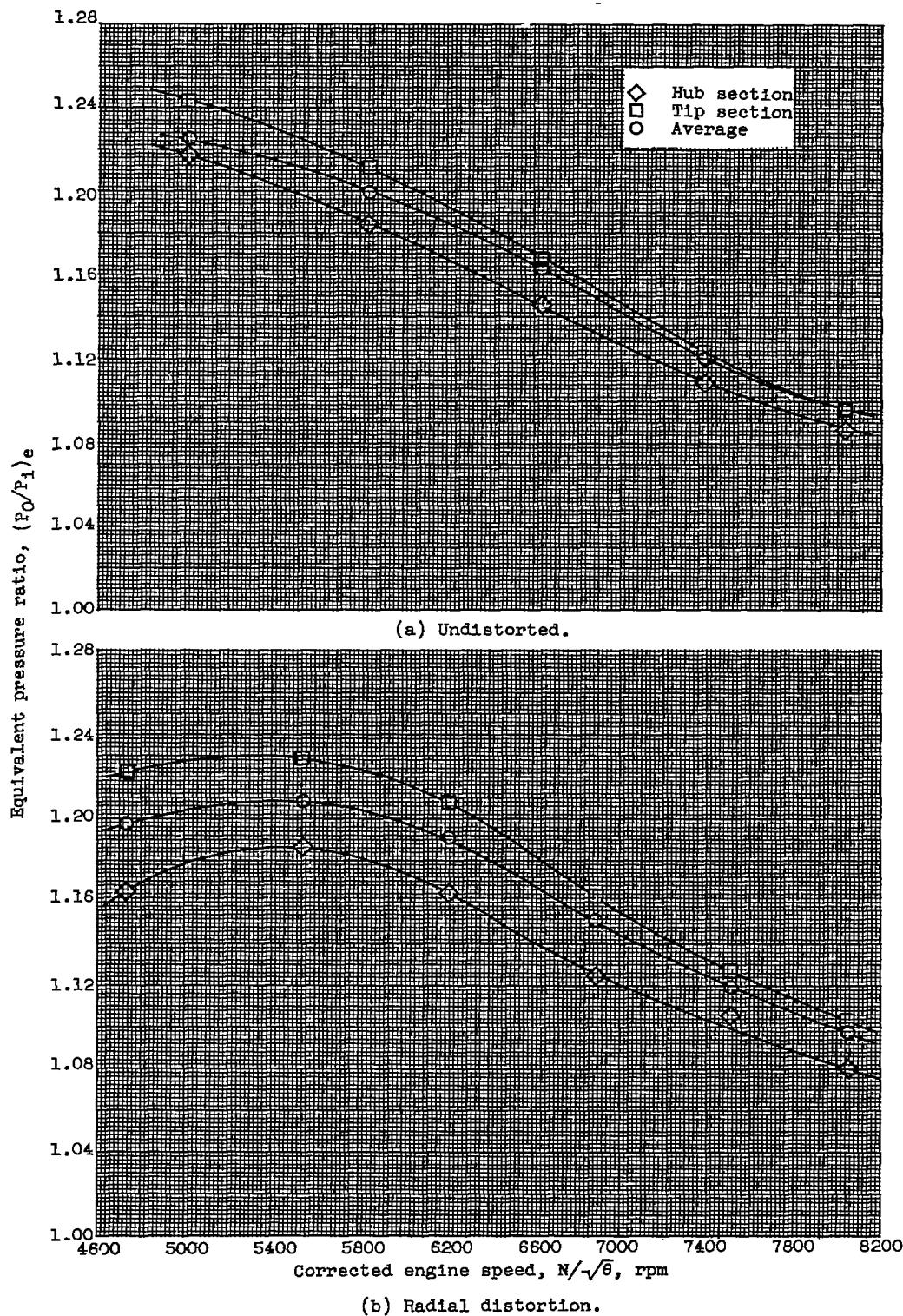


Figure 14. - Effect of radial distortion on equivalent pressure ratio at hub, tip, and average sections of stage group one to four. Closed inlet guide vanes; altitude, 35,000 feet.

CONFIDENTIAL

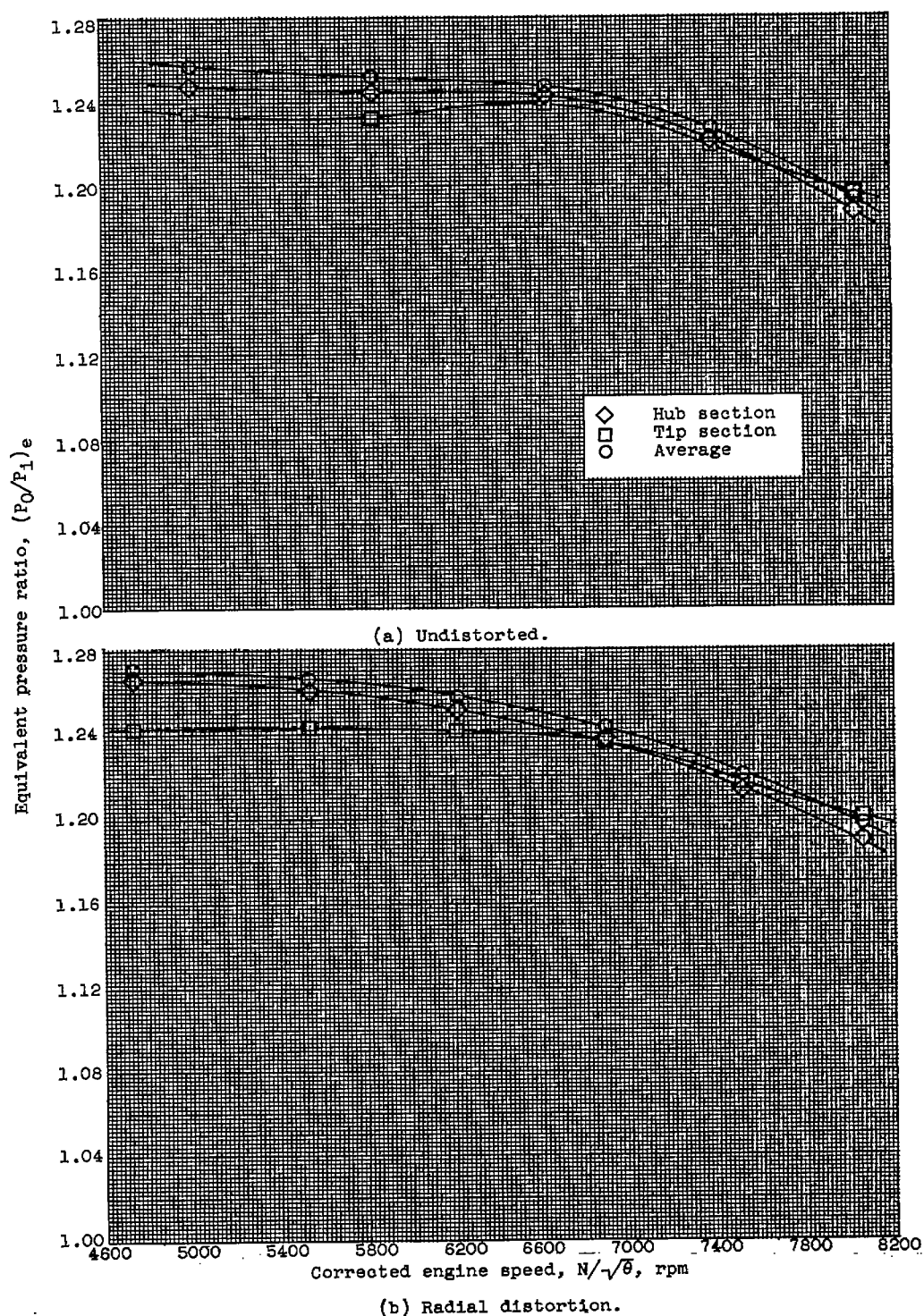


Figure 15. - Effect of radial distortion on equivalent pressure ratio at hub, tip, and average sections of stage five to seven. Closed inlet guide vanes; altitude, 35,000 feet.

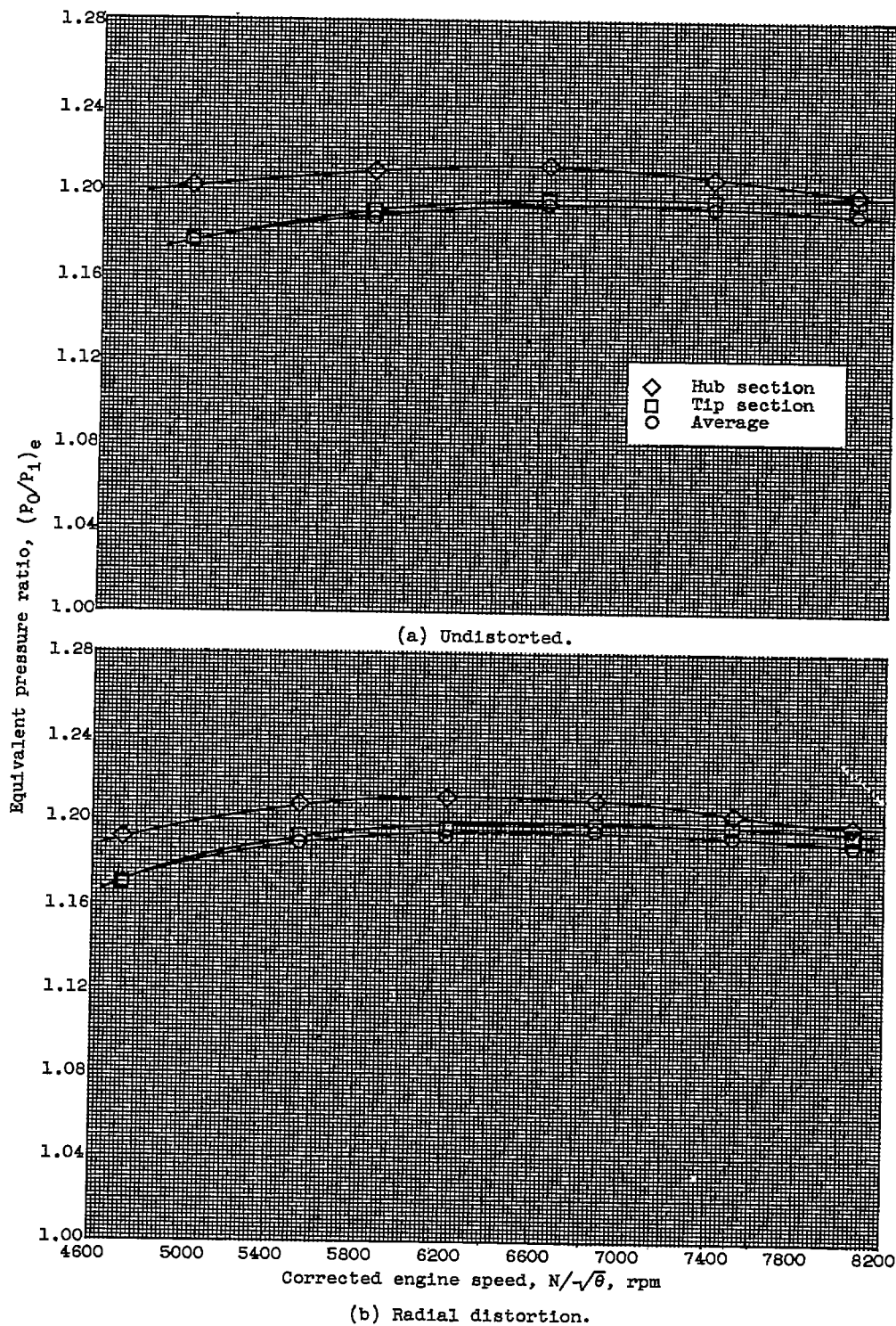


Figure 16. - Effect of radial distortion on equivalent pressure ratio at hub, tip, and average sections of stage group eight to ten. Closed inlet guide vanes; altitude, 35,000 feet.

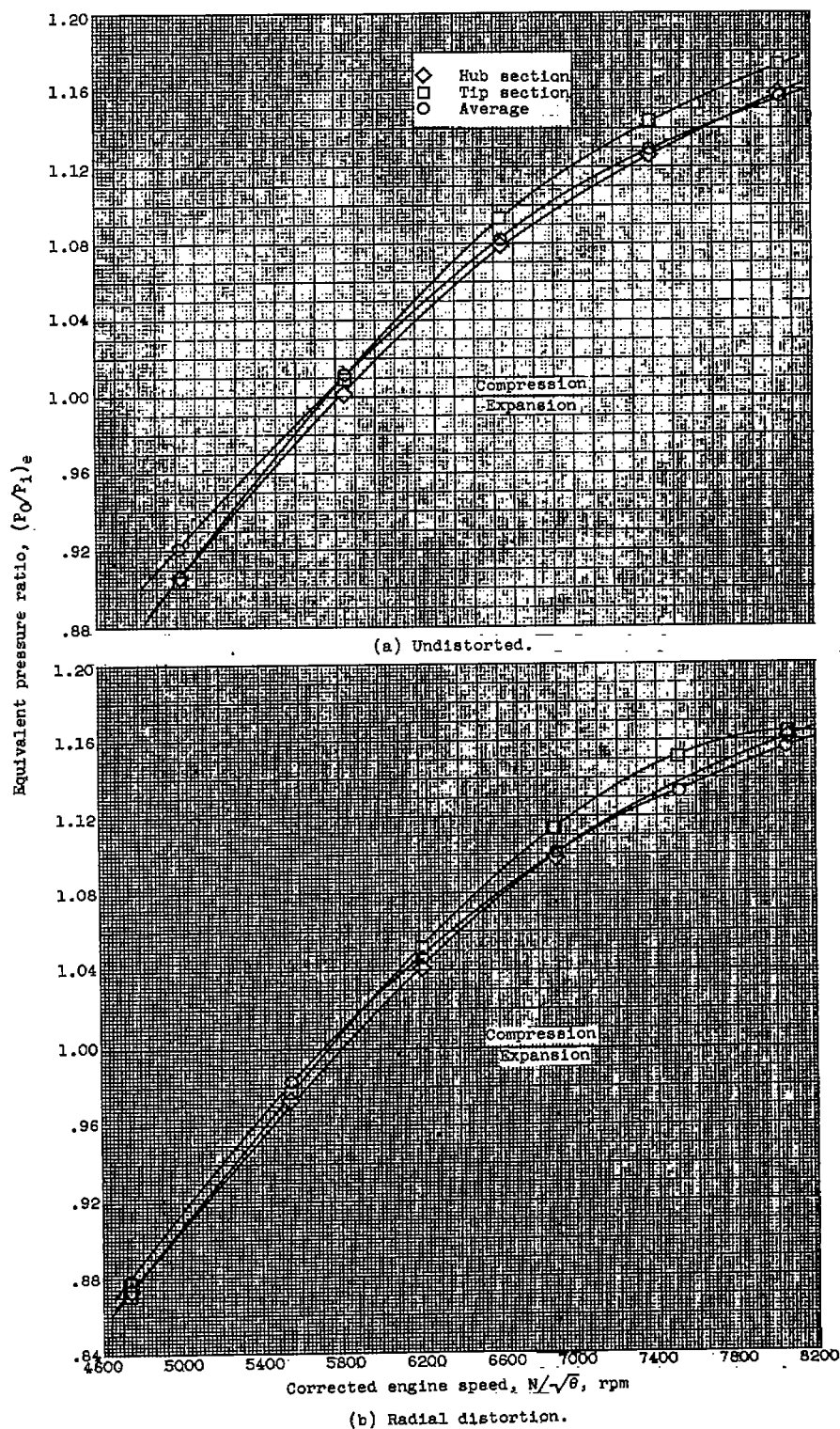
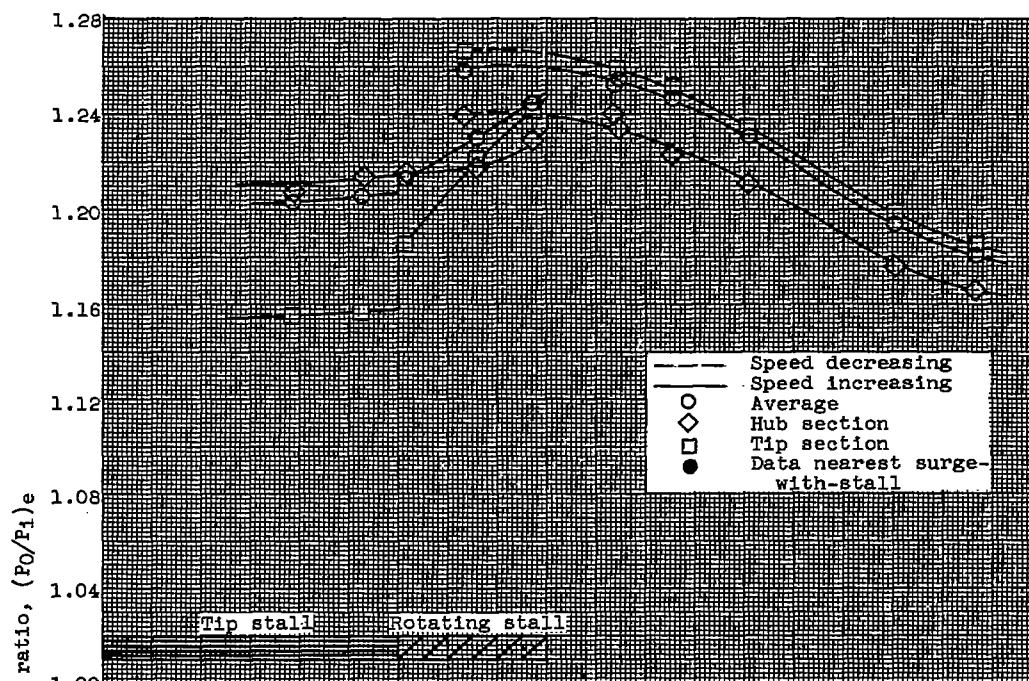
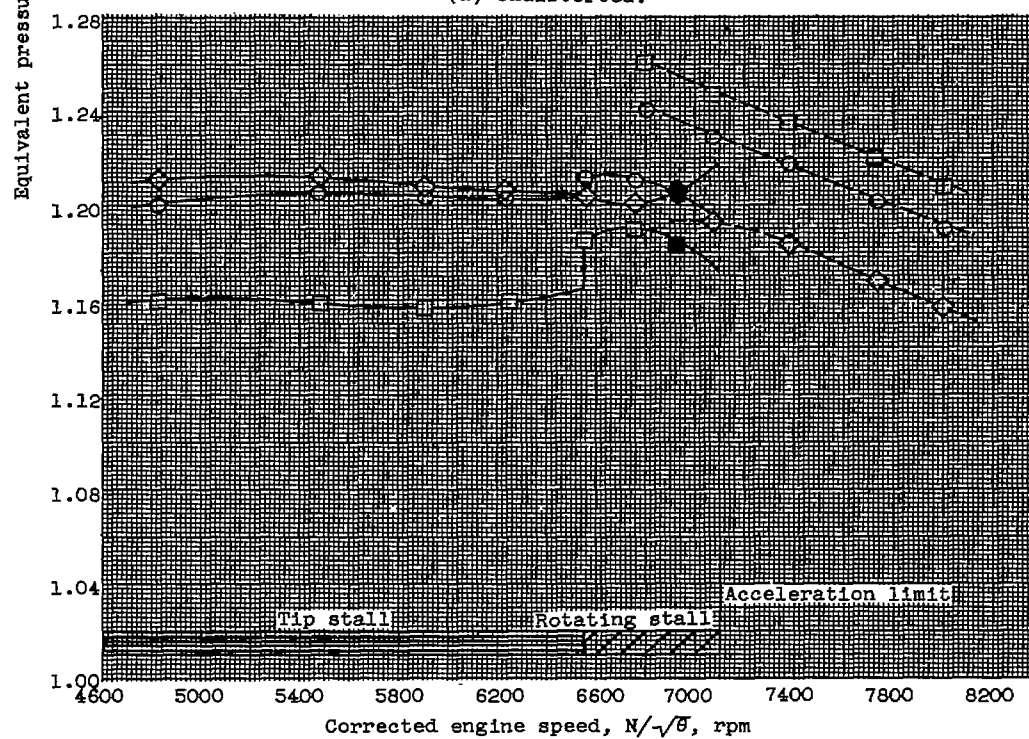


Figure 17. - Effect of radial distortion on equivalent pressure ratio at hub, tip, and average sections of stage group eleven and twelve. Closed inlet guide vanes; altitude, 55,000 feet.

~~CONFIDENTIAL~~

(a) Undistorted.



(b) Radial distortion.

Figure 18. - Effect of radial distortion on equivalent pressure ratio at hub, tip, and average sections of stage group one to four. Open inlet guide vanes; altitude, 35,000 feet.

~~CONFIDENTIAL~~

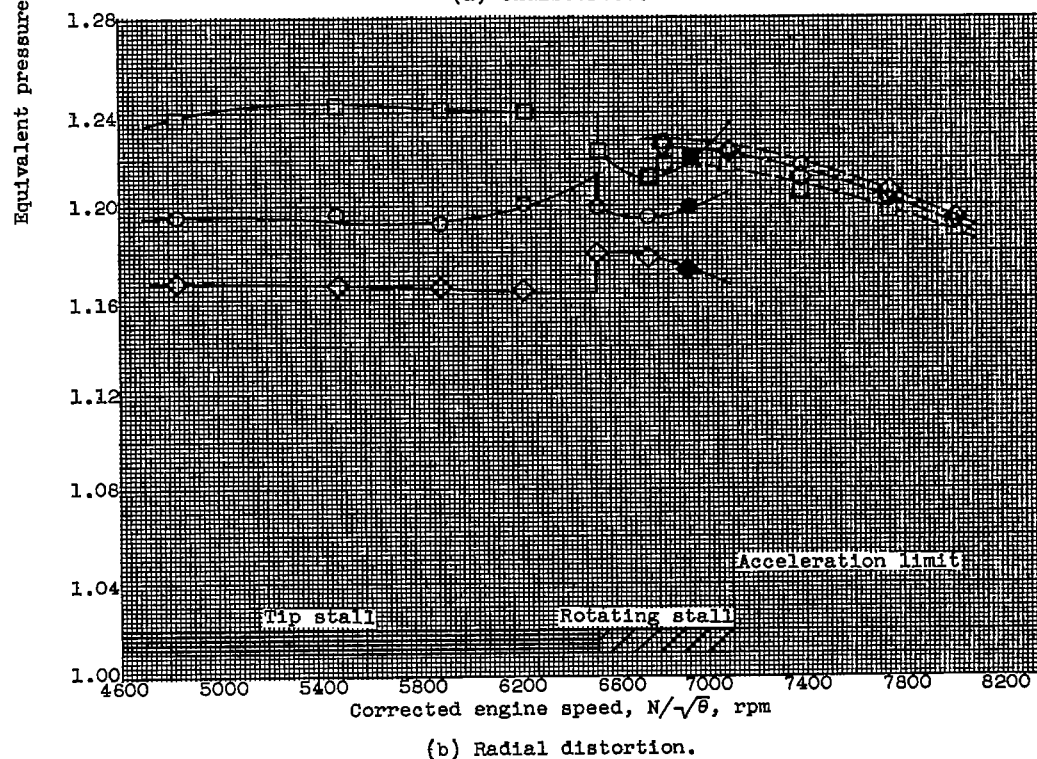
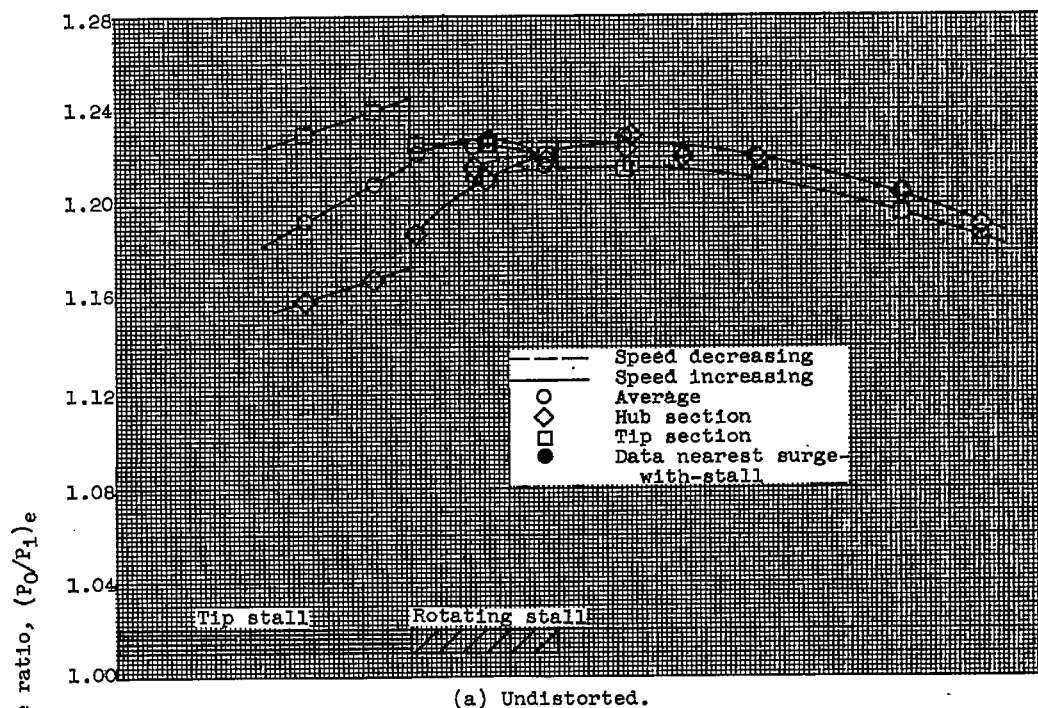


Figure 19. - Effect of radial distortion on equivalent pressure ratio at hub, tip, and average sections of stage group five to seven. Open inlet guide vanes; altitude, 35,000 feet.

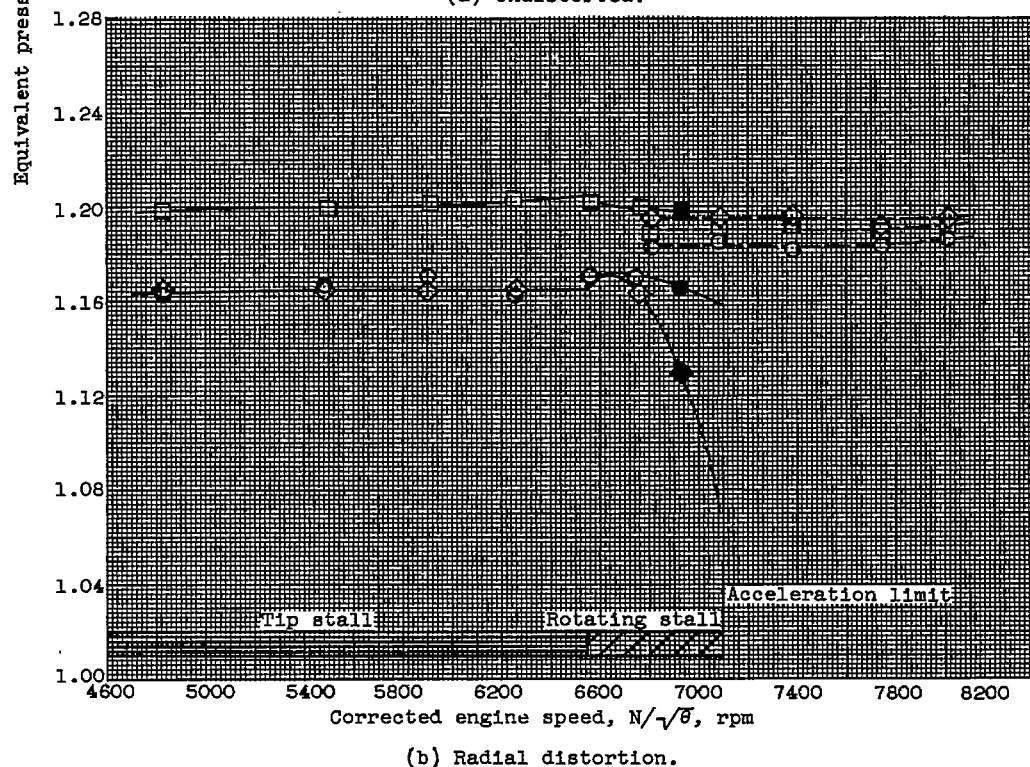
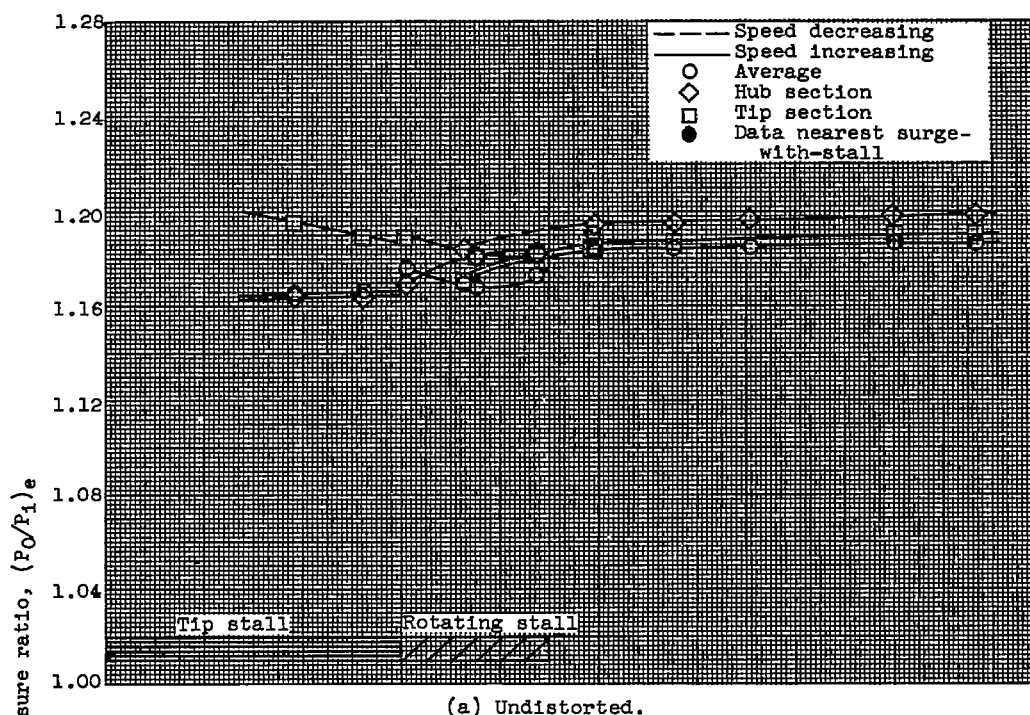
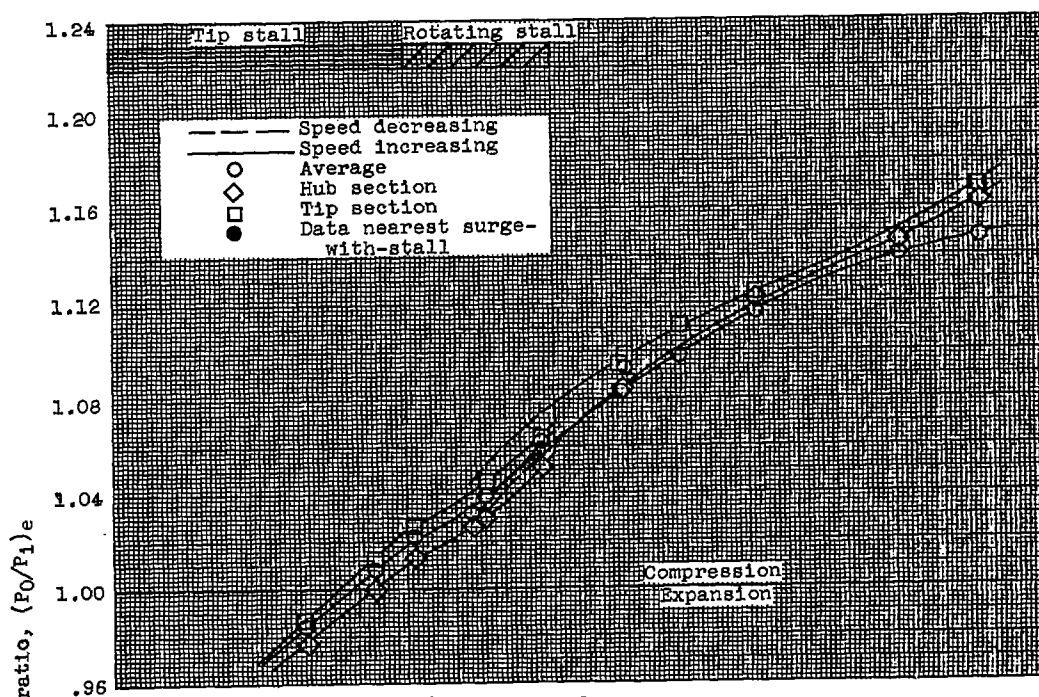
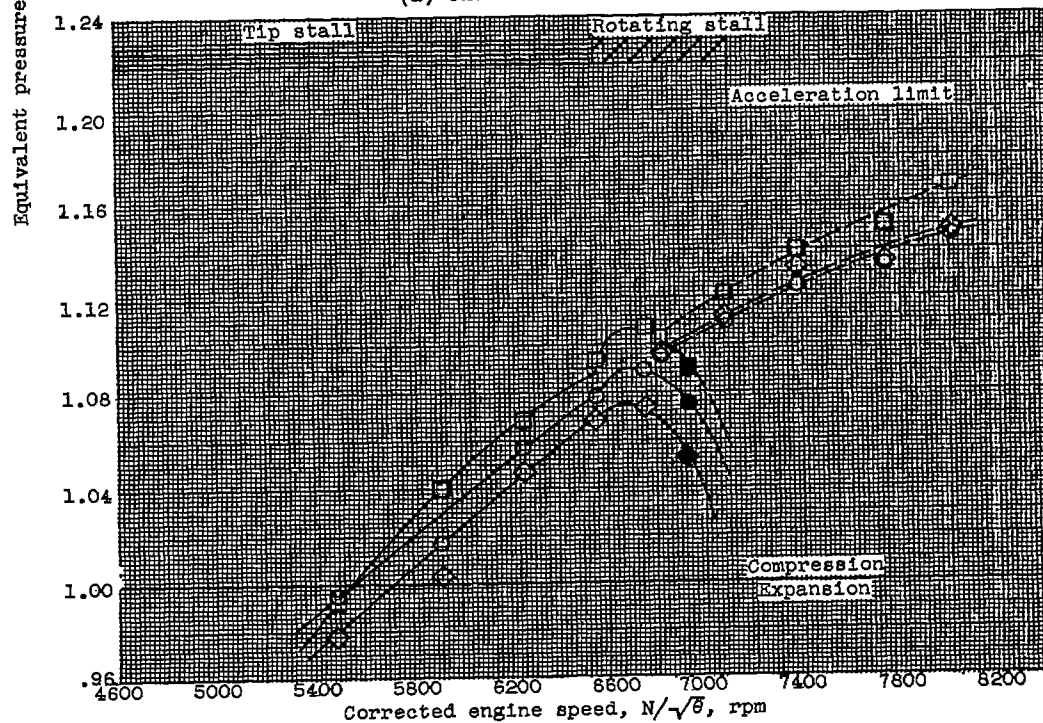


Figure 20. - Effect of radial distortion on equivalent pressure ratio at hub, tip, and average sections of stage group eight to ten. Open inlet guide vanes; altitude; 35,000 feet.



(a) Undistorted.



(b) Radial distortion.

Figure 21. - Effect of radial distortion on equivalent pressure ratio at hub, tip, and average sections of stage group eleven and twelve. Open inlet guide vanes; altitude, 35,000 feet.

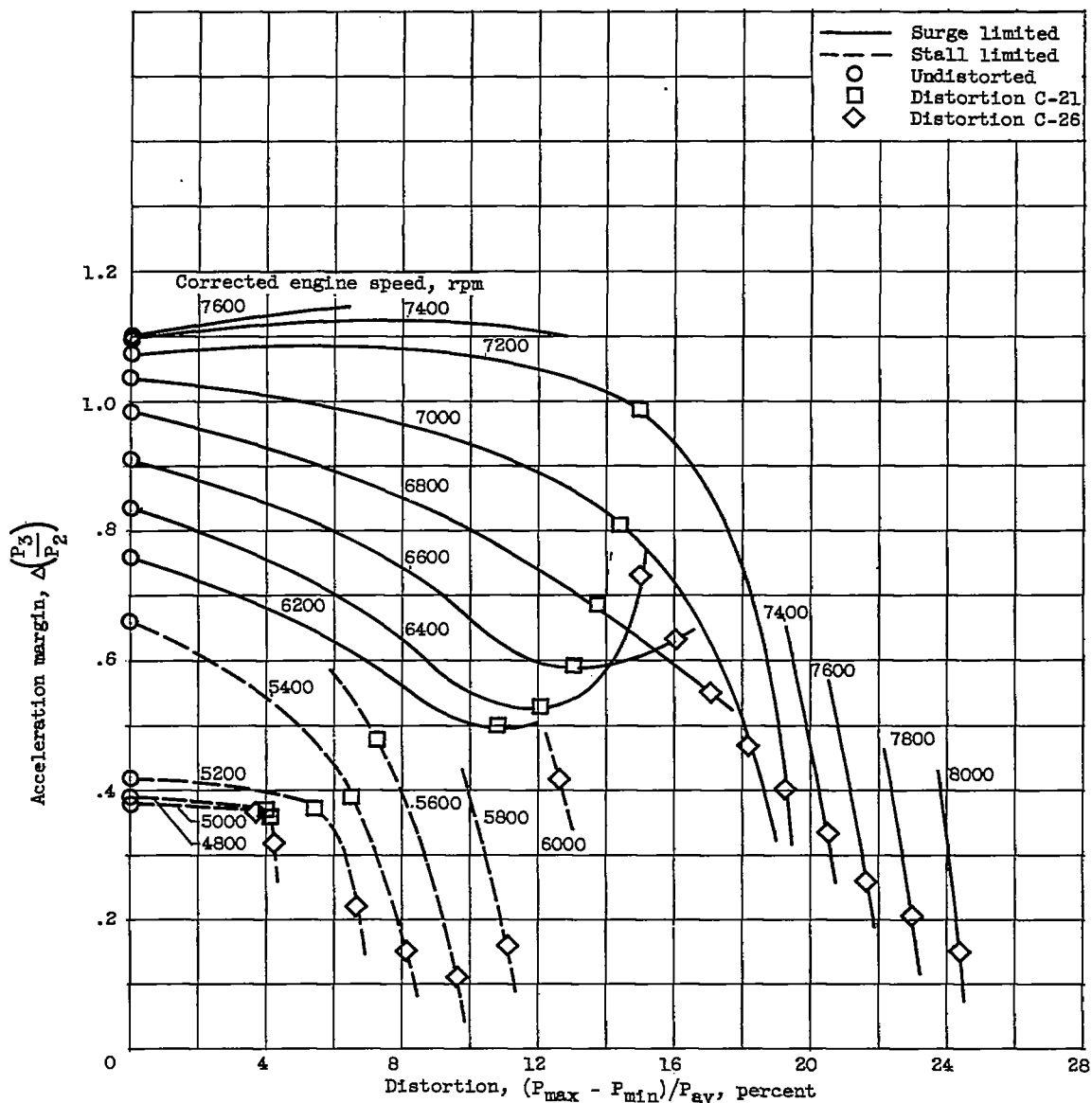


Figure 22. - Effect of circumferential distortion on acceleration margin. Inlet guide vanes closed; altitude, 35,000 feet.

NO. 3477

NACA RM E54K26

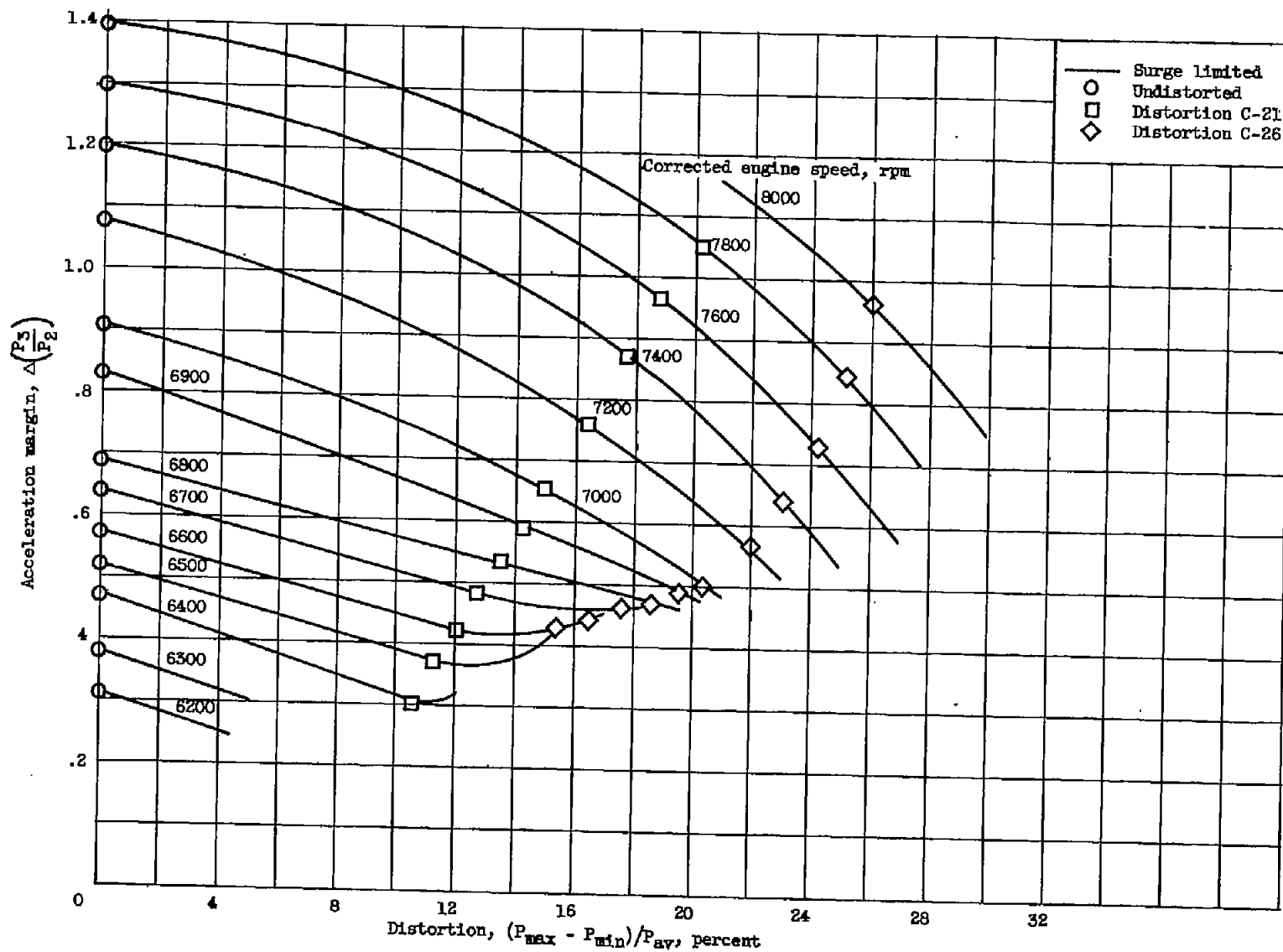
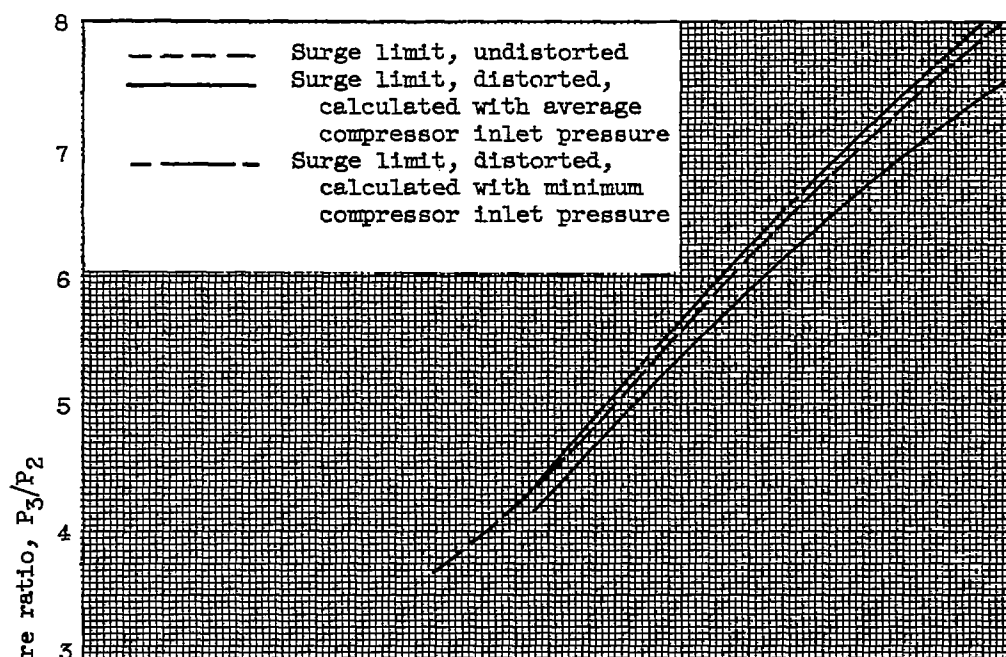
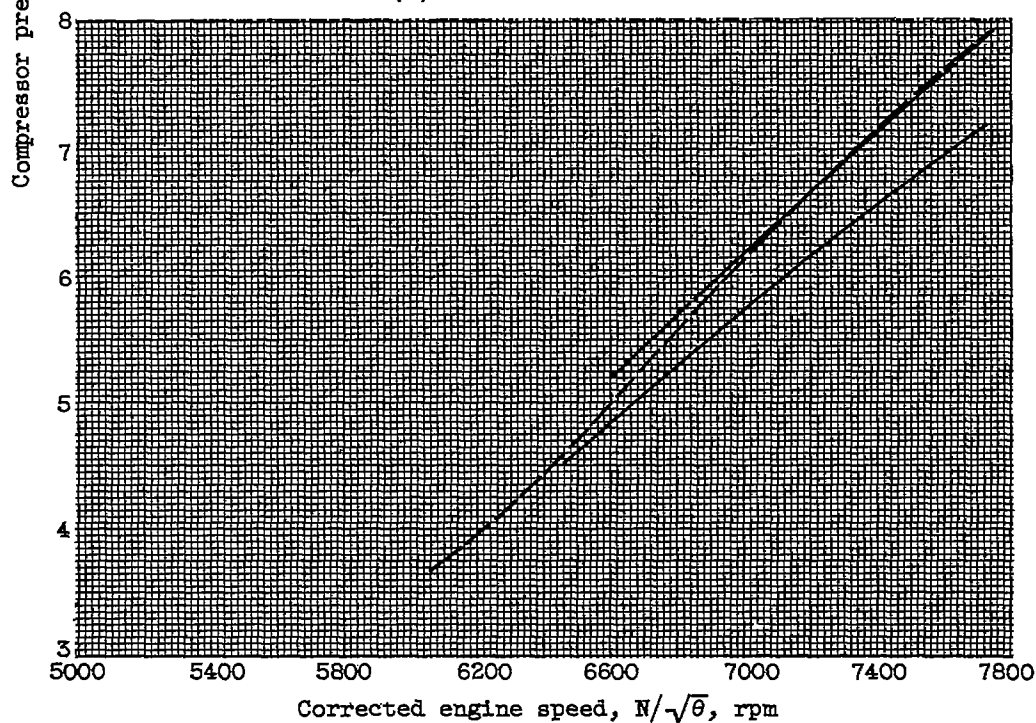


Figure 23. - Effect of circumferential distortion on acceleration margin. Open inlet guide vanes; altitude, 35,000 feet.

~~CONFIDENTIAL~~

(a) Distortion C-21.



(b) Distortion C-26.

Figure 24. - Comparison of surge pressure ratios for undistorted and circumferentially distorted compressor with minimum inlet pressure. Open inlet guide vanes; altitude, 35,000 feet.

~~CONFIDENTIAL~~

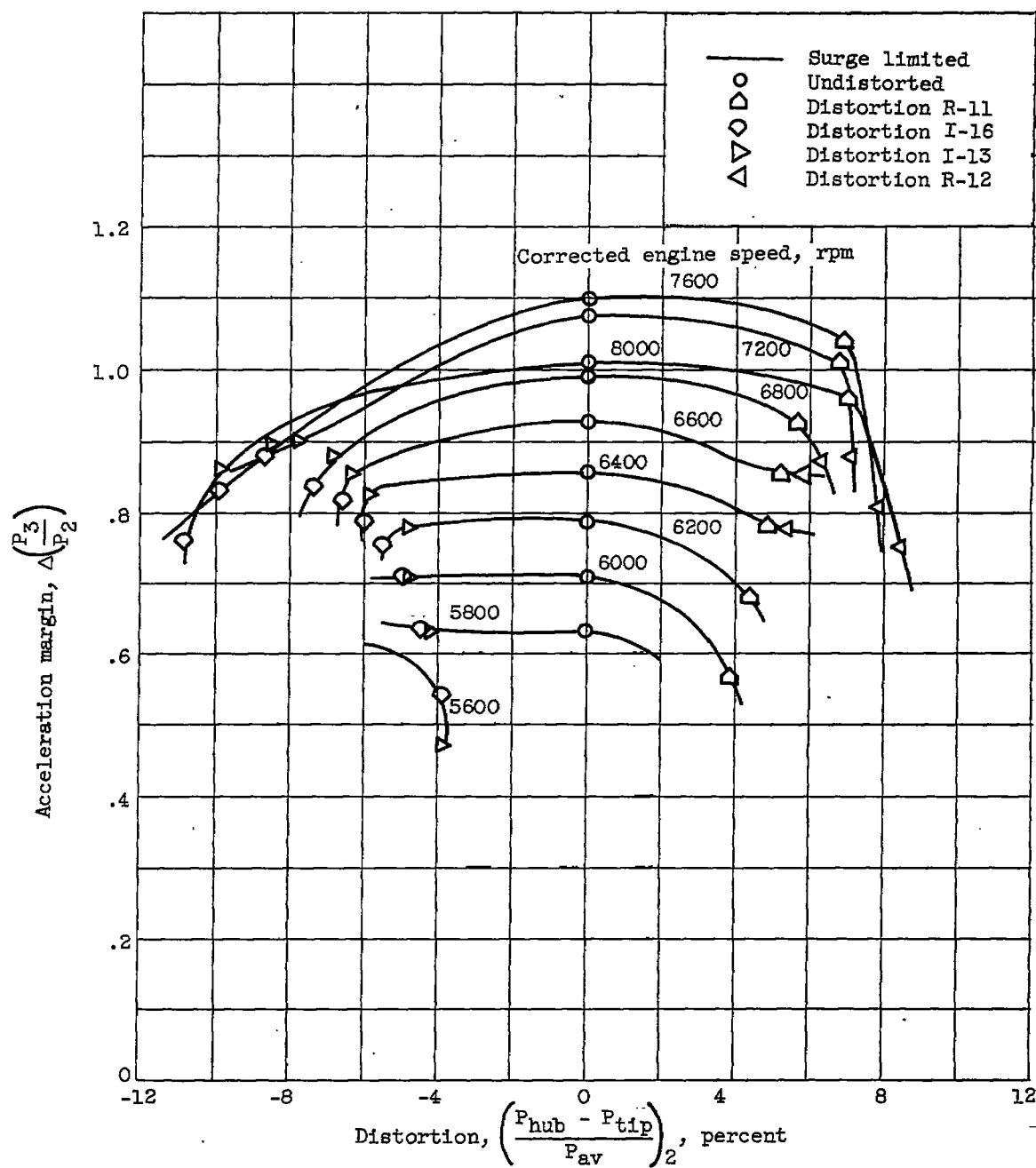
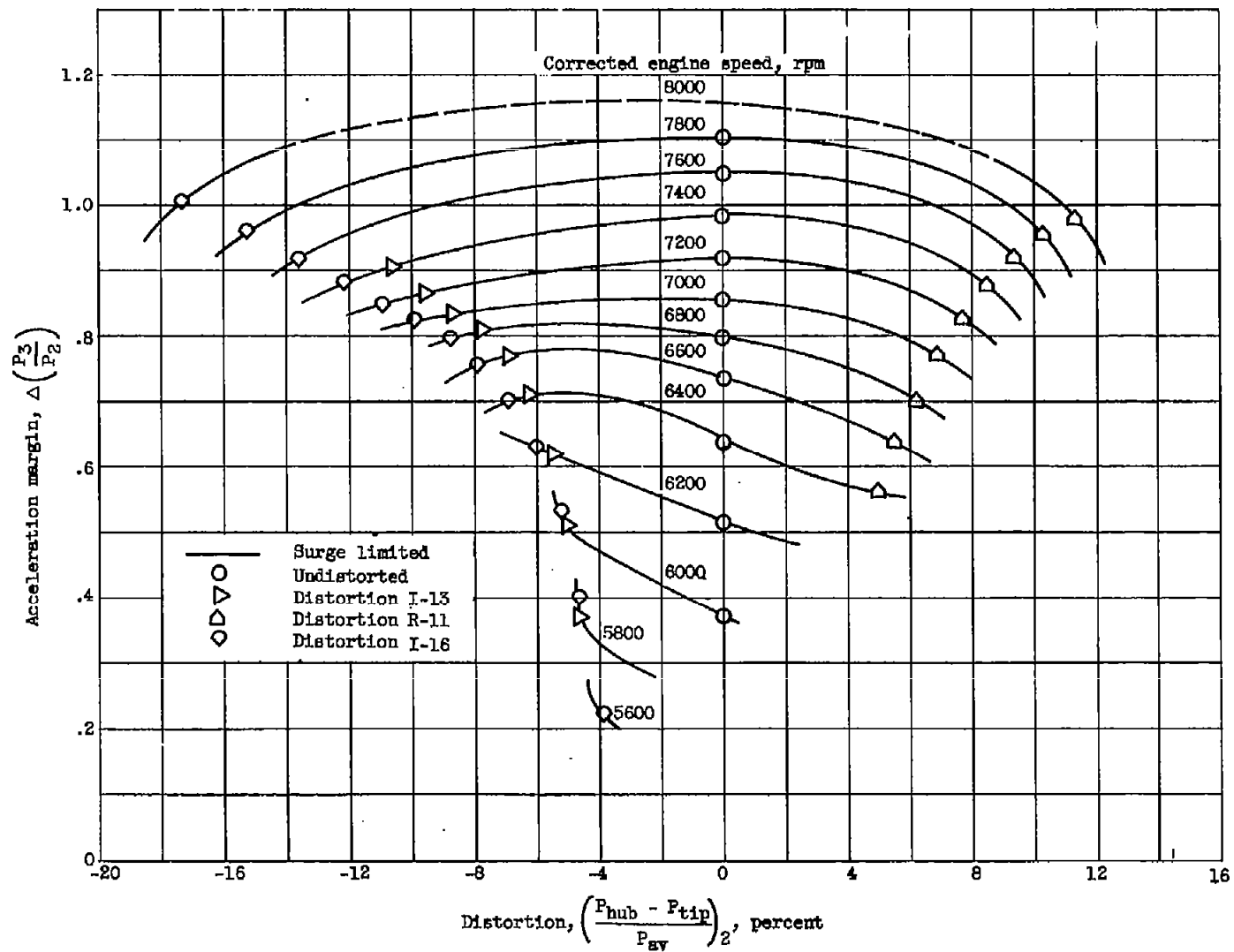
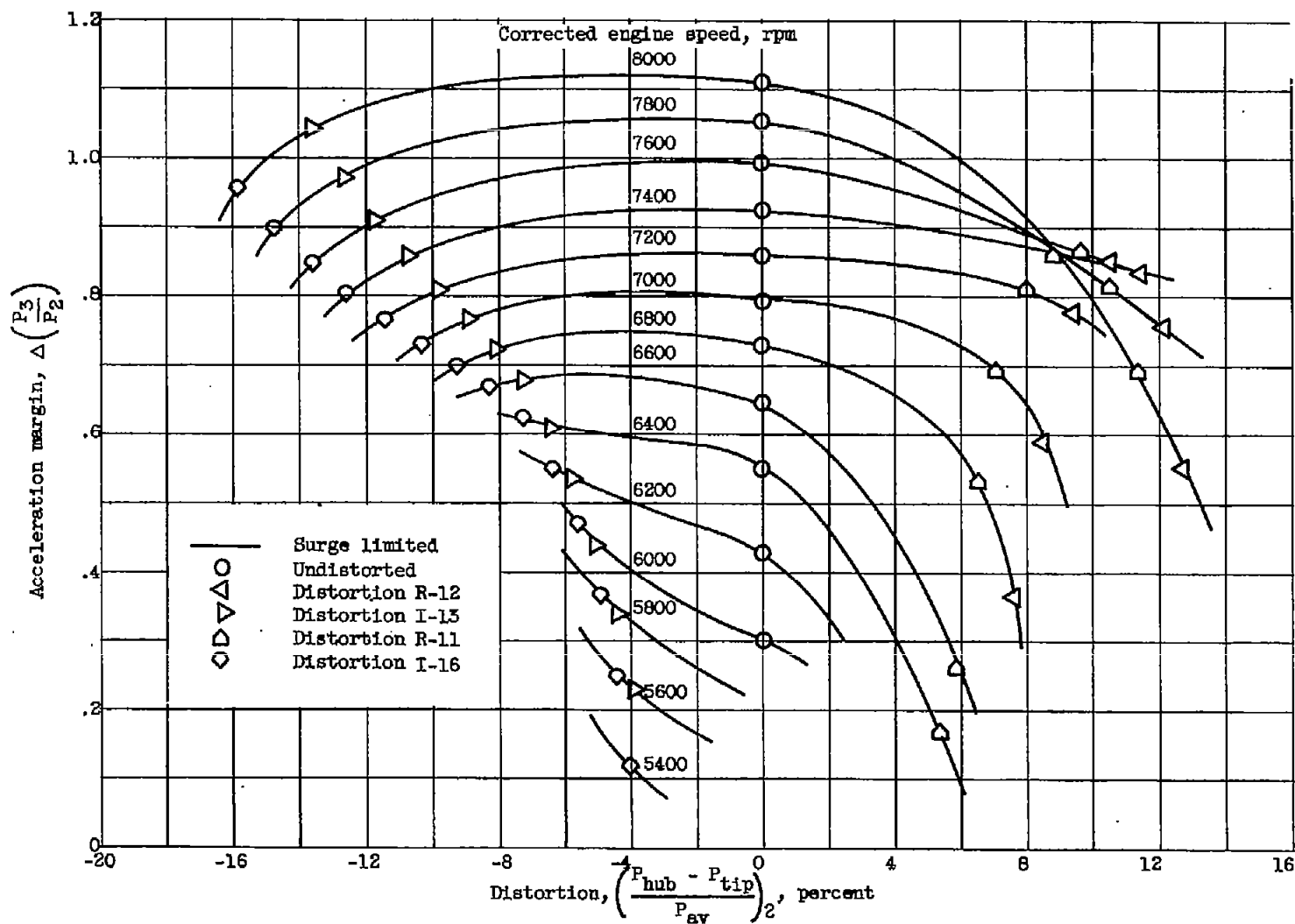


Figure 25. - Effect of radial and inverse radial distortion on acceleration margin. Inlet guide vanes closed; altitude, 35,000 feet.



(a) Simulated altitude, 15,000 feet.

Figure 26. - Effect of radial and inverse radial distortion on acceleration margin. Inlet guide vanes open.



(b) Simulated altitude, 35,000 feet.

Figure 26. - Continued. Effect of radial and inverse radial distortion on acceleration margin. Inlet guide vanes open.

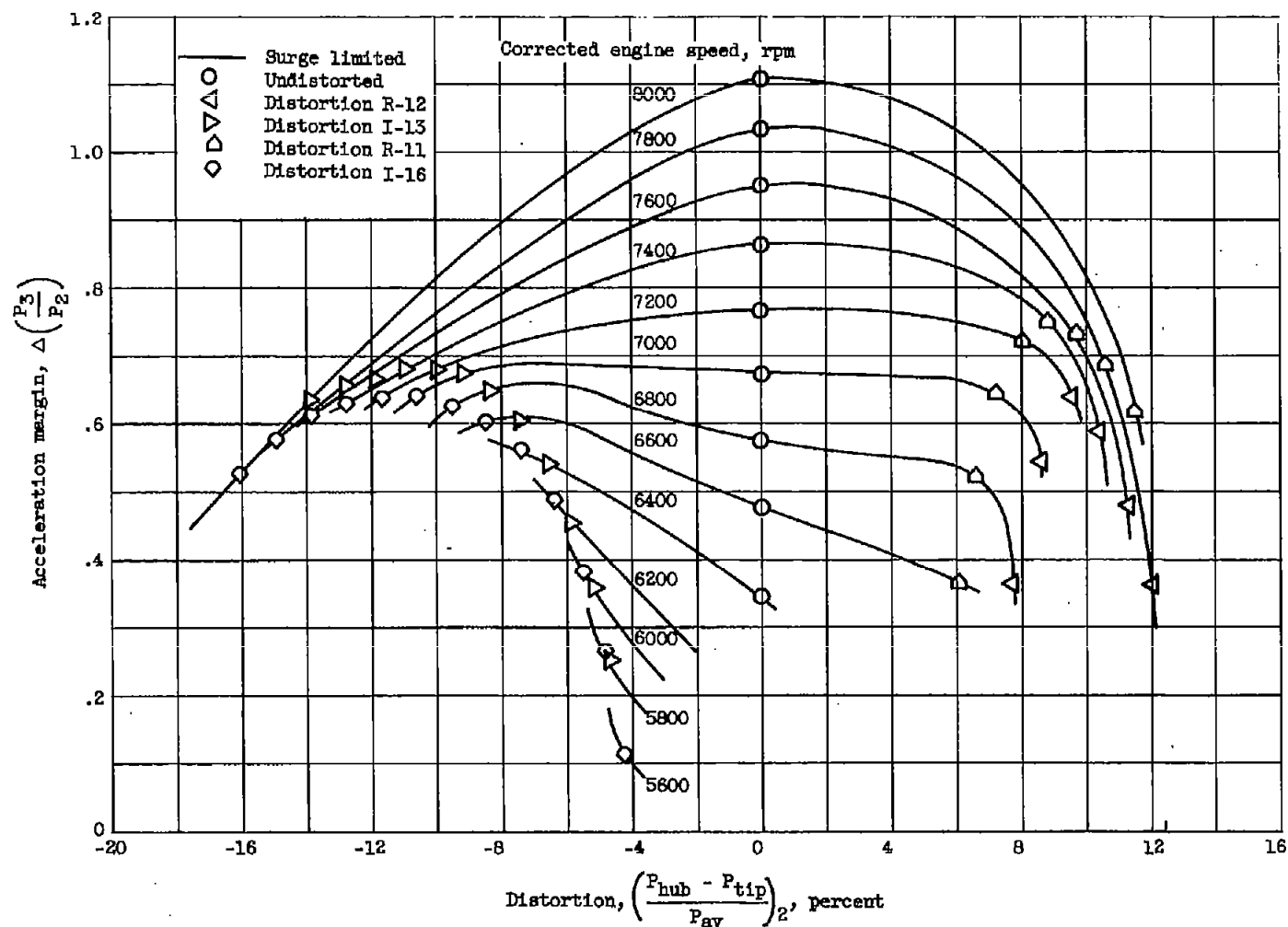


Figure 26. - Concluded. Effect of radial and inverse radial distortion on acceleration margin. Inlet guide vanes open.